AN EXPERT SYSTEM FOR SUPPORTING DESIGN CONSISTENCY BASED ON DESIGN FOR MANUFACTURABILITY

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ABSTRACT

Concurrent Engineering aims to integrate design and manufacture in order to deal with the issue of development of the lowest cost part designs by the concurrent consideration of requirements (these generally exist as sets of constraints), which arise from different product life cycle domains during the design process. This requires organisation and management of these constraints in such a way that various design analyses can be carried out to ensure the designed product is consistent with the design and manufacturing requirements. However, representing complex designs in terms of constraints and variables is difficult and time consuming. This requires an open system structure, which enables new databases to be attached easily through an effective information exchange and communication protocols.

The major aim of this research work was to develop an intelligent constraint-based design environment for supporting concurrent product development. The objectives of the research were (1) to develop a prototype system that integrates most of the design and manufacturing activities during the design process, (2) to develop a constraint-based system ensuring design consistency, (3) to structure a platform for product process optimisation, (4) to evaluate the developed prototype system through a case study.

An intelligent constraint-based system encapsulating the expertise of product life cycle issues has been developed to help designers to design manufacturable products with the existing manufacturing facilities. The system consists of a CAD solid modelling system, user interface, design representation, consistency manager module, constraint-based system, process optimisation and manufacturability analysis module, and various knowledge sources. It was designed in such a way to allow designers to design low cost products in a consistent and systematic manner and at the same time ensure the products could be manufactured with the existing manufacturing facilities. It has the capability to check that the designed component satisfied the requirements from issues of the product life cycle and avoided design inconsistencies in the early design stages. The system enabled designers to ensure overall co-ordination, control, consistency, and data integrity in order to avoid costly design iterations during the design process.

Also, the system provided designers with the ability to monitor and resolve any conflicts that may arise, and to avoid product designs that are not economic being produced. In addition, it has a user-friendly interface, which included various powerful features, such as menus for design analyses and conflict resolution, to provide designers with an interactive design environment.

The development process passed through four major stages: Firstly, an intelligent constraint-based design system for concurrent product and process design including a machining process optimisation module was developed. Secondly, the product features, processes, cost, time and requirements were represented in the format of constraints, frames, objects, and production rules in order to be utilised to accomplish different design tasks. Thirdly, production rules for the selection and optimisation of feasible processes for complex features were written, and finally, the information management system with a conflict resolution mechanism was developed to achieve consistency in information exchange and decision-making activities between the different design areas.

The evaluation and optimisation of machining processes was one of the most important aspects of these issues. It required the collection of a variety of information on different aspects of the product's life cycle. This had a significant effect on a product cost. The developed system included a rule-based process optimisation module. This module used a combination of both mathematical methods and constraint-programming techniques. It provided designers with the ability to evaluate and optimise feasible machining processes in a consistent manner, in the early stages of the design process. Consequently, unexpected and costly design iterations, which resulted in wastage of a great amount of engineering time and effort and longer lead-time, were avoided. The developed design environment was tested on an automotive component. Conclusions drawn from the system showed that the developed design environment could help companies reduction in product cost and lead time by full integration of design and manufacturing activities through ensuring a high level of overall design consistency. It prevented designers from design conflicts, provided them with the capability of making final decisions on designs quickly subject to pre-defined requirements and enabled the maximum and economical utilisation of the available manufacturing facilities.

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NOMENCLATURE

SYMBOL	DEFINITION
AI	Artificial Intelligence
B-rep	Boundary Representation
CAD	Computer Aided Design
CAPP	Computer Aided Process Planning
CE	Concurrent Engineering
CNC	Computer Numeric Control
CSG	Constructive Solid Geometry
DFM	Design for Manufacturability
DFMA	Design for Manufacture and Assembly
DMS	Database Management System
DOE	Design of Experiment
EI	Enterprise Integration
FEA	Finite Element Analysis
FMEA	Failure Mode and Effect Analysis
GT	Group Technology
HTML	Hypertext Mark-up Language
IDS	Intelligent Design System
IT	Information Technology
KBS	Knowledge Base System
KEE	Knowledge Engineering Environment
KS	Knowledge Source
LAN	Local Area Network
LCC	Life Cycle Cost
MDS	Manufacturing Design Specification
OOP	Object-Oriented Programming
PDOM	Parameter Design Optimisation Method
PDS	Product Design Specification
QFD	Quality Function Deployment

SPC	Statistical Process Control
STEP	International Standard for the Exchange of Product Model Data
VADE	Virtual Assembly Design Environment
VE	Value Engineering
VEDAM	Virtual Environment for Design and Manufacture
VM	Virtual Manufacturing
VR	Virtual Reality
VRML	Virtual Reality Modelling Language
WWW	World Wide Web

CHAPTER 1

1 INTRODUCTION

Increasing competition in the market place is challenging manufacturing industry to bring low cost, high quality and well-manufactured products to market in a shorter space of time. Today many companies all over the world have given up utilising the traditional product development approach to avoid product failure, loss of sales and profit, and declining market share. Successful product development now requires fundamentally improved methodologies for the organisation of the product development process, so as to reduce waste, and to design products in order to meet customer requirements to respond to the global competition (Kotler, 1994). Integrated product development concepts, and time-to-market are key issues in competitive success. A new product design approach called concurrent engineering has, therefore, been proposed to achieve these aims.

The roots of Concurrent Engineering (CE) date back to World War II, when shortage of resources, social and political pressures, demanded the production of better weapons in the shortest possible time, led to the tight integration of design and manufacturing activities (Das et al.,1995). The Concurrent Engineering approach was again rediscovered in the late 1970s because of increasing global competition. Concurrent Engineering has become an environment of necessity for companies wanting to compete successfully in the 1990s and beyond (Krishnaswamy and Elshennawy, 1992).

Concurrent engineering can help achieve and sustain a competitive advantage through the design of low-cost and high quality products, by the implementation of an integrated product and process development approach including various life cycle requirements such as material, processes, design requirements, optimisation, and manufacturability (Molina *et. al.* 1995). The success of the CE approach is subject to the careful consideration of product life cycle issues at the early stages of the design process. This helps to eliminate high risk and cost (Figure 1-1).

This approach deals with inconsistencies between product and process related concerns, in early stages of the design process, and proposes solutions to conflicts during product development, in order to produce reliable, economical, useful and marketable products with the best use of the available manufacturing facilities in house. This requires that specialists from different departments, in an organisation, work on product and process design to reduce the time taken for design, and establish strong links between design and manufacturing. This eliminates unnecessary efforts that can cause increased use of engineering time leading to added expense.

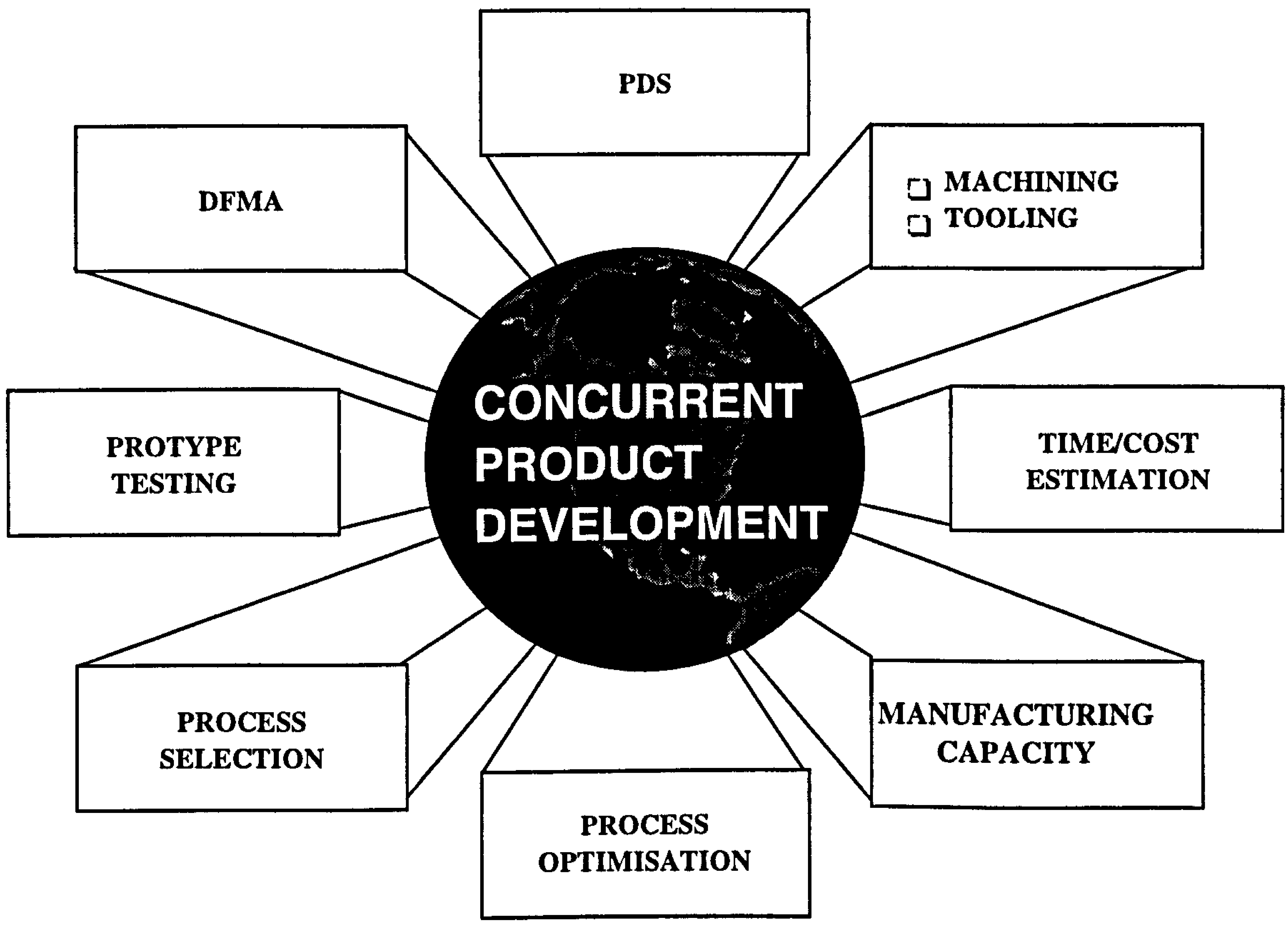


Figure 1-1 Various Perspectives in the Product Life Cycle

Thus, today a multidisciplinary team is required to achieve the implementation of CE, in organisations, to deal with the complexity of the product development process (Crow, 1994). This presents problems in managing such teams, whose members must clearly understand how to deal with any conflicts within the team, during the design process.

Practising the CE concept, within a company, needs fundamental changes in organisational structure, decision-making, information sharing, management, and conflict resolution (Wang and Wright, 1996).

Therefore, achieving the practice of CE necessitates creating a broad model for carrying out such activities concurrently during the design process. Currently, a co-operative design environment for concurrent engineering (Gunasekaran and Sarhadi, 1997, Prasad et al., 1997), information modelling and management (Eversheim et al., 1997, and Oehlmann et al., 1997), enterprise integration and management (Prasad et al., 1997, Lim et al., 1998), quality management (Ismail et al., 1997), virtual manufacturing (Lyons et al., 1997, Korves and Loftus, 1999), and process and product optimisation, and design consistency (Gayretli and Abdalla, 1999), and recycling and clean machining (ElBaradie, 1996) are the recent important issues in concurrent engineering.

1.1 Objectives of the Proposed Research

The main aim of this research is to develop a design for manufacture prototype system, which enables designers to consider product life-cycle constraints associated with design in the early stages during the design session, in order to ensure higher degree of design consistency at less cost, in shorter times and provide greater customer satisfaction.

The objectives of this research include the following tasks:

1. To develop a prototype system that integrates most of the design and manufacturing activities during the design session.
2. To develop a constraint-based design environment that ensures design consistency.
3. To structure a platform for product and process optimisation.
4. To evaluate the system via a case study.

1.2 Organisation of This Thesis

This thesis consists of eight chapters. The content of each chapter is summarised as follows.

Chapter 2 presents a literature review of related and current research areas. It starts with an emphasis on the necessity for the Concurrent Engineering approach in the design process. The survey includes a review of related areas in Concurrent Engineering and tools for supporting concurrent product and process design, Feature-based Systems for Process Selection and Evaluation, Process Time-Cost Estimation and Optimisation, Computer-Aided Process Planning, Expert Systems, Design Consistency in Concurrent Engineering. Limitations of existing approaches are discussed.

Chapter 3 describes the structure and characteristics of the proposed approach to concurrent product and process design. A description of the elements of the proposed approach is explained briefly. A working scenario for the proposed system is also described in this chapter.

Chapter 4 describes the intelligent constraint-based design system for concurrent product and process design. This is based on the satisfaction of constraints arising from different aspects of the product life cycle. The representation of design and manufacturing knowledge in the form of rules, frames, object-oriented representation and constraints is covered in detail in this chapter.

It also describes the development of the user interface for providing an interactive design environment, and the consistency management system for the management of information exchange and decision-making activities, which are needed to ensure overall design consistency in the system and design output. In addition, the integration of problem solution techniques (production rules with forward and backward chaining and OOP) are explained in detail.

Chapter 5 describes the proposed approach to cost estimation, process selection and optimisation. The estimation of process cost and time are also discussed in this chapter. Finally, a rule-based algorithm for the optimisation of manufacturing processes is presented in detail.

Chapter 6 presents a case study to demonstrate the current capabilities of the system and the significance of this research.

In chapter 7, conclusions are drawn and the overall contribution of the system explained. Finally, recommendations for future work are given in chapter 8.

CHAPTER 2

2 LITERATURE SURVEY

2.1 Introduction

This chapter presents a summary of previous research work, related to the theme of this work. Section 2.2 provides an overview of the traditional product development process. An approach to the integration of design with manufacturing is presented in Section 2.3. A definition of concurrent engineering, and reviews of research work in the area of Concurrent Engineering are presented in Section 2.3.

Section 2.5 outlines the previous research in the area of feature-based manufacturing process selection and optimisation. Section 2.6 describes research work carried out in the area of cost and time estimation of manufacturing processes.

A review of research work in the area of computer-aided process planning (CAPP), expert systems, and design consistency in Concurrent Engineering is summarised in Section 2.7, 2.8 and 2.9.

Section 2.10 presents a critical appraisal of the previous research work, and its applicability to the integration of design and manufacturing activities during the design process.

2.2 Traditional Product Development

It can be seen from Figure 2-1 that the traditional product design approach is sequential. In this approach, the Product Design Specifications includes both product specification and manufacture specification. In the early stages of the design process, manufacturing concerns are not clearly described.

Information included in Product Design Specification usually contains the constraints of design and manufacture, extracted from the customer and other available resources. When the conceptual design is completed, the next stage is the detailed design covering some of the manufacturing requirements. Although there is flow of information between stages in the traditional product design approach, it is a sequential and an iterative process, which results in high product costs and long lead-times. There is often conflict between product and process designers. Therefore, a new integrated product design approach has to be developed in order to deal with this problem.

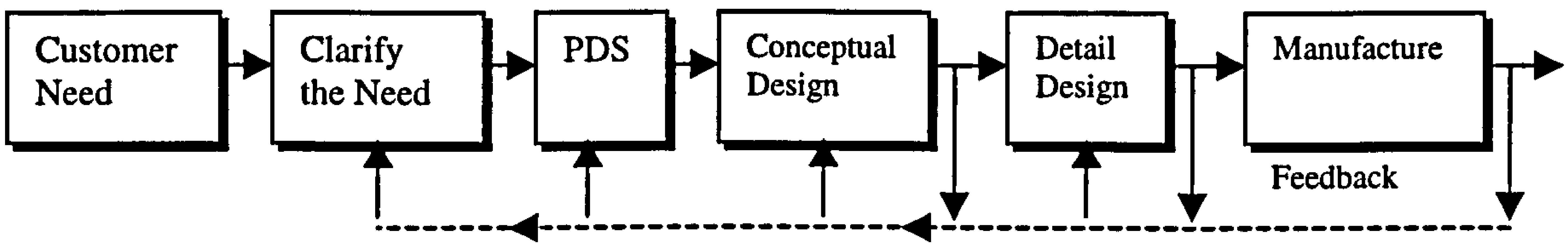


Figure 2-1 Traditional Product Development Approach

2.3 An Integrated Product Design Approach

Unlike the traditional product design approach, an integrated product design approach enables designers to consider all requirements, associated with design and manufacture, at the beginning of the design process (Figure 2-2). These requirements are included in the PDS (Product Design Specification) and in the MDS (Manufacturing Design Specification). The PDS includes customer requirements and constraints, such as cost, operating conditions, testing, life expectancy, product modifications and diversification during the product life cycle, operations, maintenance, quantity, etc. The MDS includes product features, manufacturing capacity, product volume, and process tools specification. The designer evaluates the available information in order to consider design and manufacture constraints. Using computer based-design tools, designers can have full control over the design and manufacturing data so as to update it and change it whenever it is necessary. Design alternatives, generated by the designers, are checked to see if they can be economically manufactured with the existing manufacturing facilities in order to find the most feasible solution, which is consistent with the design, and manufacturing specifications.

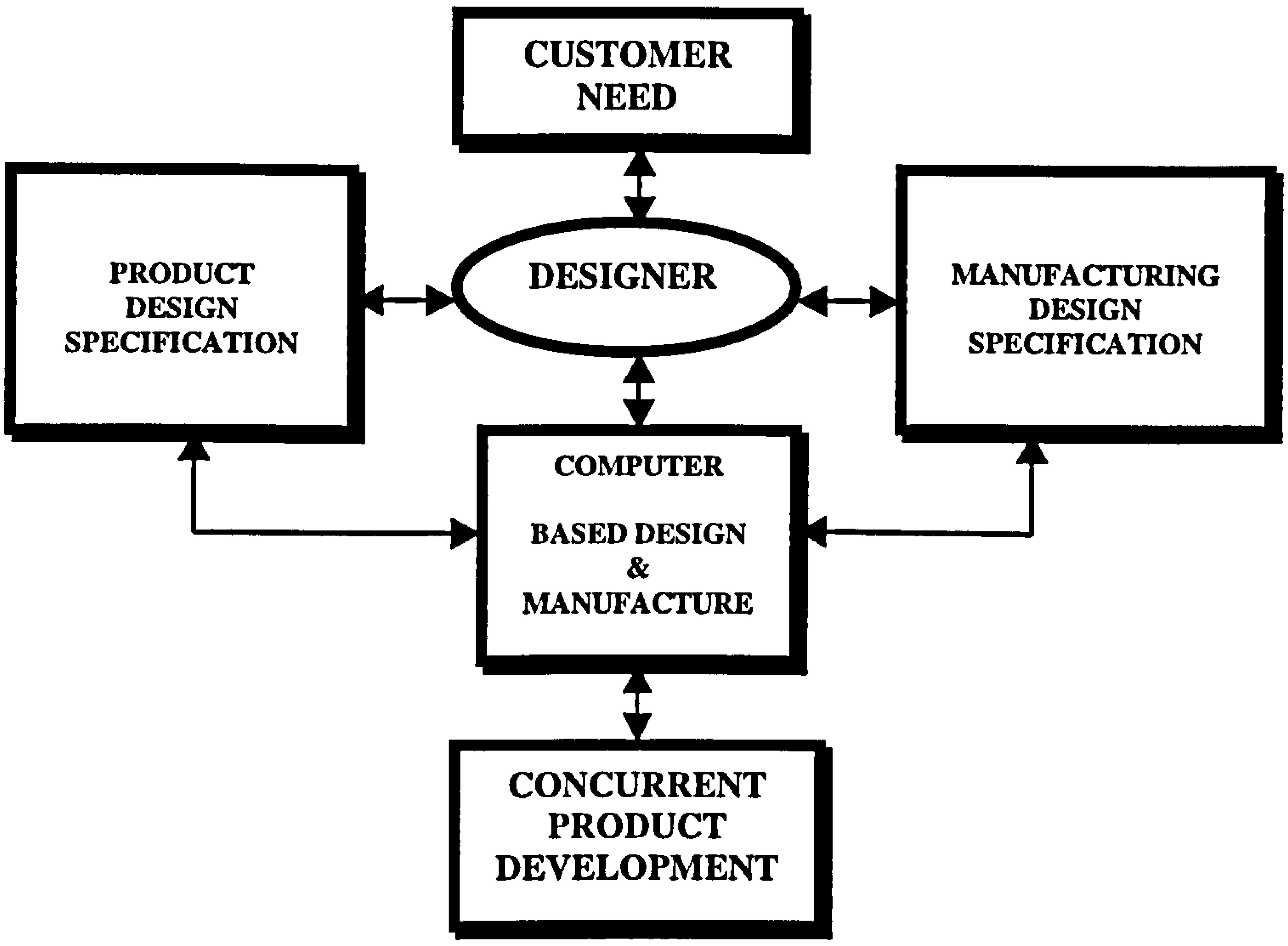


Figure 2-2 Integrated Product Development Approach

2.4 Concurrent Engineering

Concurrent Engineering is defined as a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through to disposal. This includes quality, cost schedule and user requirements (Institute for Defence Analysis Report R338, 1988). Another definition of Concurrent Engineering is that it is a systematic approach to integrated product development, that emphasises response to customer expectations and embodies team values of co-operation, trust and sharing in such a manner that decision making proceeds large intervals of parallel working by all life-cycle perspectives early in the process, synchronised comparatively brief exchanges to produce consensus (Cleetus, (1992)).

The benefits of the implementation of Concurrent Engineering are summarised as follows:

- Increasing productivity, designing products that offer high quality, reliability, less cost (Ranky, 1994),
- Improved communication, quality, less design changes, shorter time to market, reduced development cost, effective management, and increased profit (Abdalla, 1998).

A study of 103 electronic companies carried out by Duffy and Salvendy (1999), in the USA, has demonstrated, that the use of concurrent engineering reduced the time to market.

Concurrent Engineering, as a synergistic approach, aims to improve the overall design process by providing design engineers with knowledge about manufacturing and providing process engineers with what they should know about the design of product. This necessitates the early involvement and integration of various activities associated with design and manufacturing. The success of a CE approach is based on the concurrent integration of various engineering activities through well-founded methods, effective tools, dedicated teams, and effective communication (Anumba and Evbuomwan, (1999)).

2.4.1 Techniques for Supporting Concurrent Engineering

The success of a product, in the market place, necessitates concurrent consideration of all product life cycle perspectives to be taken into account in the early stages of the design process. Concurrent Engineering is a methodology for organising the product development process to reach this aim. This leads to shortening the product lead-time to the market. The integration of design with manufacture and other related concerns, such as maintenance, recyclability, and assembly, to satisfy customer requirements is of prime importance in CE. For this reason, there is a need for tools and techniques to support the CE approach, in order to fully implementing its goals.

Although, many researchers have developed tools, techniques, and methodologies for supporting CE in order to cover all product related activities and processes, the concept of CE is not yet fully established (Duran, 1995).

2.4.1.1 Constraints-Based Systems

Hashemian and Gu (1995) stated that Concurrent Engineering places emphasis on the downstream aspects of product design, that have to be considered concurrently at the design stage. A constraint-based system was developed in order to model and handle design requirements. This model uses a constraint network to model information about various life-cycle issues for its effective use during the design process. It includes a constraint and variable pool and a constraint management module. In the system, design variables have their own working constraints. When the user assigns a value to a variable, the constraint management module propagates the assigned value via the constraint network, and check for constraint violations. A valid solution is reached after a complete constraint satisfaction.

This approach has some advantages. Firstly, design knowledge can be modelled to a great extent, as a set of constraints. These provide designers with direct and active use of design knowledge during the design process. Secondly, as constraints from different aspects of product life cycle can be included in the system, concurrent consideration of design activities can be accomplished.

However, this approach has the following limitations:

1. It is difficult and time consuming to define complex designs in terms of constraints and variables.

2. There is a need for providing an open system structure so that new databases can be attached to the system easily. This needs further development of product information exchange and communication protocols.

Feng et al. (1995) developed a constraint-based system for concurrent product development. The system is based on the feature-based approach. It comprises of a feature knowledge base, a constraint knowledge base and an inference engine. Machining constraints and form features are represented as classes and objects.

Xue and Dong (1993) described an approach to new feature modelling which includes tolerances and manufacturing process for the implementation of CE concept. The feature modelling consists of design, manufacturing features, and geometrical features. A CAD system provides an environment for controlling the design process. Design object information is used to generate design alternatives. By using the feature-based design modelling, the alternatives are changed and detailed. Eventually, optimisation of the design tolerances is carried out to minimise product cost.

Abdalla and Knight (1994) developed a design environment for concurrent product and process design. Their approach ensured that products could be manufactured with the existing manufacturing facilities, in order to meet the demands of high quality and lowest product cost. The system comprised of an integrated feature-based CAD solid modelling system and an expert system, which encompassed information about manufacturing facilities and product features. A feature recognition system was developed using Constructive Solid Geometry (CSG) including basic volumes, and Boundary Representation (B-rep) such as faces, edges, and integrated with the expert system tool-kit (KEE). The developed system included design and manufacturing rules for part features and manufacturing facilities. Capabilities of the existing manufacturing facilities were also represented to achieve the CE goals. The defined constraints of the existing manufacturing facilities helped the designer to ensure parts could be produced with the available manufacturing facilities.

Alting (1992) discussed the importance of environmental-friendly product and process design, as environmental concerns are becoming more important than ever before. Since, new cost features such as disposability, ease of use, aesthetics, occupational health, etc., have emerged.

Therefore, manufacturing processes and technologies must be improved to meet environmental and social needs. He mentioned that the Taguchi Quality Loss Function could be used to estimate costs of environmental and societal requirements. He strongly emphasised that products, to be designed, had to be usable and readily disposed of.

Ishii (1992) presented a model for Concurrent Engineering design that would achieve the CE goals of communication, early design reviews, use of Value Engineering (VE), Quality Function Deployment (QFD), and Computer Aided Engineering. He stated the advantages of a computer-based system called Design Aid for Simultaneous Engineering (DAISIE), and a compatibility model evaluating design alternatives concurrently from various points of view such as process engineer, tooling engineer and design engineer.

Colton (1992) presented an integrated system called Intelligent Design System (IDS) which consisted of a CAD system (Pro/engineer) and a knowledge-based system. The IDS had a knowledge base containing manufacturing and assembly information in the form of rules. As design information was obtained from the CAD system, the expert system utilised the developed rules in order to check the product's ability to be manufactured. The expert system informed the designer of any manufacturing constraint violations. This avoided difficult problems with unnecessary manufacturing steps. Pro/Engineer allowed the designer to make modification to the part dimensions and tolerances based on the suggestions given by the expert system. The C programming language was used to develop the system. It used iconic representations. Features, which were selected from an icon menu, could be utilised to generate complex objects. Material types and stock sizes (of standard parts) were selected from the menu. The expert system then examined the manufacturability of the product (object). The IDS also contained simple static failure analysis of parts and required three types of information: CAD data, a design catalogue and a knowledge base. The CAD data system contained a broad range of information about object length, width, height and orientation.

The design catalogue included cost, weight, strength features of standard parts and fasteners, and mechanical properties of materials and manufacturing processes. The knowledge-base contained rules and heuristic data related to design, and manufacturing methods and constraints. The expert system used these rules and heuristic data to ensure the manufacturability of components. To manage the huge amount of data in the system, a Database Management System (DMS) was needed for the effective use in the expert system and updating additional information about design and manufacturing.

Dong (1992) introduced a new engineering feature-oriented CAD methodology providing integrated feature representation, tolerances, feature relations, relationship between feature and tolerances. The methodology used the accuracy graph to represent dimension and tolerances.

Thurston and Carrahan (1993) introduced an intelligent system for integrating design and manufacturing activities into intelligence-based system in order to evaluate the design for its manufacturing cost. The CE concept required that various design analyses were carried out concurrently during the design process. To achieve this, consideration of activities related to design and manufacturing facilities had to be evaluated. The Taguchi method was a very good tool for relating design parameters and manufacturing process with the quality of the products. It utilised an experiment-based system for analysing design parameters including product geometry, material, production process, temperature, etc.

The best design was the one that minimises expected loss, because of incompatible variations within the manufacturing process. These unavoidable variations (i.e. tolerances, feed-rate and customer requirements) had to affect product quality and robustness as little as possible. Their proposed expert system contained objective and subjective rules. The objective rules included design configuration concepts, materials, and production process meeting defined design performance requirements. The subjective rules were related to acceptable design values and attributes (cost, weight, etc.), and trade-off between attributes and user behaviour to uncertainty.

Design optimisation was not only reducing weight of components but also determination of manufacturing planning, time/cost, and process selections. CE necessitates determining design and manufacturing optimisation (cost, weight, tolerances, features and machining).

Constraint-Based Systems have been used for several design applications such as material selection for automotive components (Sapuan and Abdalla, 1997), and representation of life-cycle requirements in the form of constraints for effective use during the design process (Gayretli and Abdalla, 1998).

2.4.1.2 Design for Manufacturability and Assembly (DFMA)

Subramanyam (1989) described a model called Co-operative Product Development which included participants, representation and activities. Their proposed model included an environment that involved humans and computer-based design tools. This was an environment where designers used computer-based systems to represent development of objects such as product specification, product designs, process designs, etc. They outlined a conflict resolution strategy via negotiation, and emphasised the need for new computer-based environments to implement the CE approach.

Schrage (1992) described a case study where Concurrent Design co-operated with Total Quality Management (TQM). A new model helicopter design was proposed using both CE and TQM. Concurrent product development required several issues to be considered; a top down design approach and a system engineering management plan, multidisciplinary team, team continuity, application of QFD (practical engineering optimisation), design bench-marking and soft prototyping (Design by feature), experiments to confirm high risk predictions (QFD, and SPC: Statistical Process Control), shared computer knowledge (Corporated focus on development), etc. In this case study, the CE approach was used to identify problems and key features of the design. On the QFD matrix, customer requirements, design specification, production requirements were shown.

Computer programs such as CATIA (3-D Modelling, Configuration Analysis) were used in the analysis of the design characteristics. The optimisation of the final configuration was carried out via the Taguchi parameter design optimisation method (PDOM). To control the design tasks and allocate resources, the critical path method was used.

By using CATIA, 3-D model and configuration were developed to understand how the customer attribute matches the proposed design. Unigraphics was used to provide 3-D-surfaced and solid modelling of each part in the helicopter. The Taguchi PDOM simulations were used to simulate product performance and manufacturing, and minimise risk items. They concluded that CE is most effective in early stages of the design process and that open communication with customers was vitally important.

Cutkosky and Tenenbaum (1990) described a methodology for concurrent product and process design supported by a computational framework where the designer, in a manufacturing department, provided manufacturing information to the product designer. This methodology, consisted of SE, team design and rapid prototyping, was implemented by a system called First-Cut using a CAD system, CNC equipment and a knowledge base system. They also discussed the limitations of feature-based systems.

There are limited product features on a CAD system. They suggested that a constraint-based system was necessary in helping the designers to manage constraints, and emphasised the importance of modern computer science and AI technology to establish the link between design and manufacturing.

Ellis et al (1993) developed a design for manufacture software environment for supporting Concurrent Engineering. The proposed model provided the designer with product designs by considering manufacturing requirements. They stated that the DFM environment should provide the designers with reliable and timely advice on design and manufacture of parts to the designer, and it should also support the generation of manufacturing information. Therefore, the model included mechanisms for achieving associations between product information and manufacturing process and resource information. This model was limited to the turning processes.

Ikonopisov et al. (1994) described a CE approach to design for assembly and manufacture. They mentioned that Lucas plc had developed a computer-based expert system that asked suitable questions about functions, handling and fitting of every component. The system asked the designer if each component was necessary or not. The proposed model included a DFA&M Analysis System for providing product design-connected decisions, a knowledge base, an explanation system and a user interface. KAPPA-PC as an expert system toolkit was selected to build the knowledge-based system. The database provided materials data, assembly and manufacturing data. The explanation system was very useful to explain deductions and answers to questions. The designer used the expert system tool-kit KAPPA-PC via MS-Windows 3.X software. The DFA&M system was very useful to reduce number of components and production cost.

Gupta et al. (1995) described the current approaches to automated manufacturability analysis. He stressed that the performance criteria for manufacturability analysis should include:

Scope: the scope of manufacturability analysis should cover a variety of manufacturing issues such as new materials and processes.

Accuracy and reliability: if the results of manufacturability analysis were not sound this could cause considerable delays and iterations, and financial loses.

Correctness and completeness: the mathematical and computational foundations using geometric algorithm were inadequate.

Integration: analysis system should interact with other DFM software.

Speed: as design is an interactive process, analysis system should generate realistic design analysis and give feedback in real time.

Sophistication of feedback: feedback provided by the system should be corrected and effectively presented to the designer.

Based on the above criteria, the DFM system should address the following issues;

1. Ability to handle multiple processes.

2. Alternative manufacturing plans.
3. Virtual enterprises and distributed manufacturing.
4. Process models and virtual manufacturing.
5. Manufacturability rating schemes.
6. Accounting for design tolerances.
7. Automatic generation of suggestions for redesign.
8. Product life-cycle consideration.
9. Making use of emerging technologies.

Velay and Tabeshfar (1995) developed a computer adviser for integrated design and manufacture. They focused on the development of a fully integrated system incorporating solid modelling system and Finite Element Analysis (FEA) with a manufacturing adviser in order to provide the designers with performing an accurate and rapid optimisation of design and manufacture.

2.4.1.3 Taguchi Approach

Ismail et al. (1997) carried out a survey of the quality management practises used in the manufacturing sector in Ireland. They pointed out that companies, who had implemented TQM, achieved better performance. The Taguchi approach focused on producing products, which were functionally acceptable, within both economic tolerance, and the available manufacturing equipment. Quality was defined as satisfaction of the customer expectation during the product life cycle. Failure to achieve this meant quality loss. Customer dissatisfaction with the product caused a decrease in market share, and an increase in marketing and advertising costs. This failure lead to companies' loss of reliability, and hence avoidance of new products by the customer. The Taguchi method was used during each stage of the design process. Many design alternatives had to be generated instead of one during the conceptual design stage (system design stage).

Each alternative was evaluated from customer point of view, the engineering characteristics and the manufacturing perspective. Product and process factors affecting product performance were taken into account during parameter design stage. Any design and process factors, which are difficult and costly to control, had to be considered to make the product robust (Dean and Unal, 1992).
The Taguchi method combined with QFD, and FMEA (Failure Mode and Effect Analysis) could be used together to identify these product and process factors such as cutting speed, depth of cut, and feed-rate). Critical component tolerances played an important role in product cost. Thus, the Taguchi method considered tolerance selection by experimentation.

Suri and Otto (1998) developed an integrated system model (IMS) for providing designers with an understanding of manufacturing capability, not in terms of manufacturing constraints but in terms of variation. This system could provide designers with the selection of combinations of design and manufacturing variables, which result in the minimum variation for the product. System design, parameter and tolerance design were the major tasks in Concurrent Engineering. They had a direct impact on product cost, time and quality. For this reason, Taguchi approach was a useful tool that should be incorporated into the concurrent product development.

2.4.1.4 Quality Function Deployment (QFD)

QFD is a powerful tool for analysing various design tasks such as market analysis, manufacturing and process planning. Engineers generally focused on more technical characteristics of a product rather than customer requirements. The aim of QFD was to establish link between these design tasks, and help identify how their requirements could affect each other. Customer requirements as a starting point should be translated into engineering characteristics. This philosophy is called " listening to the customer voice". Since, QFD requires increased concentration on product quality during each stage of the design process, QFD analysis should be carried by designers working in different departments of a company.

Kapur (1992) asserted the need to develop the right quality characteristics, which were a measurement for customer satisfaction. He suggested the following characteristics:

1. Reducing the value of the quality characteristics such as noise level, harmful effect, etc. Ideal target value should be as close to zero.
2. Increase the value of the quality characteristics such as strength, life, reliability, etc. Ideal value is as large as possible without increasing product cost.
3. Ideal values of the quality characteristics such as dimensions, voltage, viscosity, clearance, etc. Ideal target value is ideal value.
4. Dynamic values of the quality characteristics such as customer requirements. Target values should be changed subject to the voice of the customer.

He also suggested that further improvement in quality could be achieved to keep variation to a minimum to make the product insensitive (robust) to the sources of variation such as environment and manufacturing imperfection and control product tolerances within acceptable limit and cost.

Krishnaswamy and Elhennawy (1992) proposed a model for Concurrent Engineering that included the concept of Quality Function Deployment, reverse engineering and virtual reality. The QFD was a basic tool for transforming customer requirements into engineering characteristics. The use of QFD has some common problems associated with it:

- Customer requirements and all subsequent stages of QFD may be misinterpreted by different people,
- Information loss,
- Different team work was needed to meet different requirements.

In order to solve these problems, Concurrent Engineering deployment was proposed. It comprised a product development team, a virtual reality module, a manufacturing module and QFD. The main aim of this approach was to enable the design team to translate the customer view into physical reality.

Downlatshahi and Ashok (1997) presented a methodology for the integration of Quality Function Deployment (QFD), and Design of Experiment (DOE) in a concurrent engineering environment. They suggested that the proposed approach could lead to improved process, shorter lead-time and less product cost.

2.4.1.5 Failure Mode and Effect Analysis (FMEA)

FMEA is a powerful tool for CE and is primarily concerned with potential events that could lead to product failures. FMEA should be carried out near the end of the design phase, either using computer programs or manually, before the product had the opportunity to fail in use. It is a quality tool and requires a team of engineers, managers, and others to get to know the actual system. Product failures can occur in various stages of product life cycle such as design, manufacturing, service and assembly. Thus, FMEA must be incorporated into the design phase to avoid product failure.

2.4.1.6 Value Engineering (VE)

One of the fundamental aims of concurrent engineering is to manufacture products at the lowest possible cost. Value Engineering (VE) as a cost reduction technique, helps in achieving this aim, by redesigning and changing the existing products. The design process does not only deal with creating new design alternatives, but also re-designing and modifying the existing product designs. Important aspects of Value Engineering are to reduce cost without reducing product value, eliminating unnecessary components without adding complexity, improving on its functionality, performance, and appearance and reduction in weight without increasing product cost.

The Value Engineering method searches for cost, function and value of each component of a product. The method considers the elimination of any function and its components, reduction in the number of parts and operations, simplification of component features, simplicity of assembly, consideration of different materials and manufacturing process, and standardisation of all components if possible.

Any components used in large numbers, such as fasteners, are also reduced to lower total cost. VE is a useful tool in CE and can help increase value of product without increasing product cost or reduce cost without reducing product value.

2.4.1.7 Virtual Reality In Design and Manufacture

Manufacturing systems are complex entities, which include people, products, processes, information systems and various data, and storage systems. The complexity requires systems to be modelled by using a variety of views and modelling formalisms. Design and proper integration of the system functions need multiple perspectives and models to be considered concurrently. However, existing computing environments do not allow this to be achieved in an effective and intelligent manner (Krishnamurthy et al, 1998). Virtual reality environments are increasingly used in industry for realistic simulation of new manufacturing processes before they are tried on the factory floor.

Virtual reality (VR) is a way that allows human beings to visualise, manipulate and interact with computer systems and complex data. Loeffler and Anderson (1994) defined VR as "a three-dimensional, computer generated, simulated environment that is rendered in real time according to the behaviour of the user". Many applications of VR have been carried out in product design and manufacturing. Virtual Manufacturing (VM) environments as a VR application have been developed in order to facilitate realising potential benefits of VM in manufacturing. The aim of VM is to provide manufacturers with a capability to manufacture products in the computer in a way that a maximum sense of reality for the user can be achieved. The use of Virtual Reality in design and manufacturing provides the following benefits:

Affordability: reliable cost and process capability information that can affect design and management decisions.

Quality: more producible designs, and higher quality work instruction to support manufacturing.

Producibility: easily generated high quality prototypes without reworks.

Flexibility: rapid product changes.

Shorter cycle time: the ability to go into production directly.

Responsiveness: rapid respond to customer requirements.

Customer relations: increased customer participation (VM User Workshop Report, 1994).

VM can help to simulate the manufacture and assembly of products, including associated processes and tooling. It also allows consideration of all variables in the production environment from processes to enterprise transactions by the visualisation of processes, process planning, scheduling, assembly, purchasing, etc. In addition, VM can be used to generate many manufacturing alternatives, scenarios, and optimise the design of product and processes for a specific aim such as DFMA. Research work has been carried out, in the area of VR applications, to various manufacturing domains such as virtual reality for layout planning of manufacturing cells (Koryes and Loftus, 1999). They presented a framework of a VR approach to the planning and implementation of manufacturing cells in which the planner entered the modelled world of the application. They stressed that the visual capability of VR could help the planning process, and that current planning methods were limited to two-dimensional. Three-dimensional modelling systems provided visual representation of the cells without the full user interaction.

Krishnamurthy et al (1998) developed a hybrid manufacturing system-modelling environment using Virtual Reality Modelling Language (VRML). This language used a file format such as HTML, which made it portable across platforms without difficulties. An environment for manufacturing system modelling had been developed for the fabrication facilities domain, which focused on machining processes.

It comprised of three levels: physical processing level (machines, toolings), information level (computers, monitors, networks), and system architecture (functional architecture of the manufacturing system). This environment had many useful features and was very suitable for the requirements of manufacturing system modelling.

Lyons et al. (1997) emphasised that VR, for prototyping, enabled designers to generate digital prototypes and evaluated the products completely before a physical prototype of the product was made. This could significantly shorten the time to market and increase a company's competitiveness. They described the creation of virtual environments for design software systems. These systems were VEDAM (Virtual Environment for Design and Manufacture) and VADE (Virtual Assembly Design Environment).

Fu and East (1999) presented an approach for supporting the design review process of architect/engineering (AE) offices that used technologies developed for the World Wide Web (WWW). This approach, called the virtual design review, provided a group of reviewers with the ability to work simultaneously on a three-dimensional representation of an incomplete building model. It helped to improve the way reviewers work in three significant ways as follows: 1. handling (viewing, retrieving, and storing) information, 2. facilitating interaction between reviewers, and between reviewers and designers, 3. changing the role of reviewers in the design review process by providing autonomous or semiautonomous agents capable of executing parts of the design review process. Also, it provided a flexible, open, and robust environment for interaction.

2.4.1.8 Enterprise Integration

Manufacturing and processing technologies are advancing rapidly. It must be recognised that many of these technologies will be costly to utilise and no single company will possess all the necessary expertise. Therefore, manufacturers and institutions are now undertaking co-operative technology development in order to share risks, costs and expertise.

This often requires international co-operation, which has to be properly managed in order to improve manufacturing operations, enhance international competitiveness, and lead to technological breakthroughs via market-driven research and development (R&D).

The use of enterprise integration (EI) methodologies and tools in manufacturing companies has enhanced business competitiveness in ways such as shorter lead-times, higher product quality and reliability, less waste and lower product cost. This is based upon the principle of EI that needs enterprise functions to be organised into a unified whole in order to improve communication, collaboration and co-ordination, hence, enhancing overall enterprise performance, decision making, and delivering higher efficiency and competitiveness (Lim et al. 1998).

Watts et al. (1998) examined how companies can use virtual reality (VR) technology to help to make them become more innovative. VR has some unique characteristics, which can help companies from three perspectives that are common to most innovative organisations: a capacity to experiment in depth; involvement of all in the innovation process; and an ability to capture ideas generated in the innovation process. However, some obstacles need to be overcome before VR performs to its potential. Since, the aim of concurrent engineering is to involve the integration of people, systems, and information into an efficient and responsive environment, integration of computerised systems is necessary to achieve automatic knowledge capture during the development and life cycle management of products, and automatic knowledge exchange between different computer systems of organisations. Solutions to these issues are product data standards and enterprise integration frameworks. The International STandard for the Exchange of Product model data (STEP) allows a complete, unambiguous, computer-readable definition of physical and functional attributes of a product during its life time. Concurrent engineering, via information technology (IT), and standards provide the power to meet this new challenge (Carver and Bloom (1991)).

Stader and Jarvis (1998) described a toolset for enterprise modelling that focused on the use of Artificial Intelligence (AI) techniques in order to cover the requirements of enterprise modelling, and the tools for supporting it. Various AI techniques were used in their research programme range from knowledge representation, process modelling to simulation techniques, intelligent workflow, and co-ordination technology. This research work was based on agent-based architecture.

Kim (1999) highlighted the need for intelligent agents to help information retrieval and decision making. They could provide users with the support ranging from designers to manufacturers, and from salespersons to customers. A computer software agent should have greater functionality than merely data retrieval or broadcast simple information.

In particular, an intelligent agent should execute routine tasks autonomously, extract new knowledge from different databases, and improve its own performance through experience. He also addressed critical issues related to the development of such agents such as general architecture, and the deployment of a learning agent for industrial planning.

Murgatroyd et al (1998) developed a framework and methodology to provide dynamic change for manufacturing enterprises that wanted to remain competitive, and adapt their business processes and the associated resources and information systems. They proposed that there was a need for business process visualisation and an improvement framework that enabled a wide range of company personnel to participate in the design process, so as to contribute to improved processes and significant improvement over previous design practice. Further research work that focused on enterprise integration can be found in Weston, 1998.

2.5 Feature-Based Systems for Process Selection and Evaluation

Manufacturing the form features of a product usually has the highest effect on the consideration of machining a product. The minimising of total product cost necessitates that the evaluation of manufacturing cost of these features be carried out as early as possible during the design stage. A mechanical part cost comprises process cost, labour cost, machine overhead, tool cost and tool change cost.

Manufacturing process cost is directly related to the form features of the component. For mass production, it is necessary to produce a very detailed manufacturing cost estimation. Rough manufacturing cost estimation should be sufficient for small to medium batch production volume to provide a useful estimate of manufacturing cost.

Gupta et al. (1994) presented a methodology for generating and evaluating alternatives process plans during the design process. It used form features to generate process plans. Their techniques involved three major steps:

- Generating a CAD design for a part.
- Generating alternative operation plans for the part.
- Evaluating the generated plans subject to:

    Machining tolerances.

    Processes cost and time (set-up times not included).

Sheng and Srinivan (1995) developed a multi-objective process planning system in Environmentally Conscious Manufacturing. It was a feature-based approach. Once manufacturing form features were obtained, machining processes that could produce these features were selected. The system had two steps for process planning. The first step was the macro planning level in which interactions between features and their effects on process planning were determined. The latter step was micro planning in which different process paths were generated for each feature. The system enabled consideration of mass and energy calculations for the process sequences, and it selected the processes and sequences that had minimum energy consumption while at the same time it led to an environmentally conscious product design.

Han and Requicha (1995) presented a feature finder for generating a part description in terms of manufacturing form features by using information from a variety of sources. It provided designers with the description of a part through manufacturing form features such as holes and slots.

Vancza and Markus (1994) developed a feature-based process planning model for the consideration of manufacturing processes and resources, conflict detection and resolution via suggestions, optimisation of the manufacturing through an algorithm, and generalisation of the plans by leaving out incidental detail. Process selection consisted of four steps:

1. Component description.
2. Choosing reference features.
3. Selection of alternative processes.
4. Generating precedence constraints.

The model used the constraints to optimise the process plans by reducing machining alternatives of each form feature.

Feature-based techniques have been used in many areas of manufacturing such as fixture design (Pham and Gologlu (1997)).

Gayretli and Abdalla (1999) developed an intelligent design environment that enabled designers to incorporate all product and process related activities into the design phase at an early stage of the design process. One of the most important aspects of these activities was evaluation and optimisation of manufacturing processes. The developed model focused on manufacturing processes optimisation using a combination of mathematical methods, feature-based cost estimation, and constraint-programming techniques. This approach enabled designers to evaluate and optimise feasible manufacturing processes of components in a consistent manner as early as possible during the design session.

This helped to avoid unexpected design iterations that resulted in wastage of a great amount of engineering time and effort, which in turn resulted in longer lead-times. Applications of other techniques to process planning such as case-based approach and petri-net model can be found in Champati et al. (1996) and Kiritsis et al. (1994).

2.6 Process Optimisation and Cost Estimation

The total cost of engineering a product consists of design, machining, assembly, tooling, testing, etc. One of the main problems confronting manufacturers is the need to produce products at lowest cost in order to obtain more market share than their competitors. The cost of the product can be determined at the early stages of the design process. Therefore, designers' decisions on product functions and features play an important role in the product cost. It was pointed out that over 70% of the total product cost was considered during the design stage (Ou-Yang and Lin (1998)).

Dewhurst and Boothroyd (1988) presented an early cost estimation model for product design for efficient manufacture (DFM). The model consisted of two steps. The first step was to identify the appropriate materials and manufacturing processes for the part. The second step was to carry out the detailed design of the individual components that is consistent with process and material capabilities. They suggested that availability of manufacturing cost information was important to make whole judgements in the choice of materials and processes as early as possible during the design process.

Downlatshahi (1992) proposed a product design optimisation approach to the design of products in concurrent engineering environment. The approach utilised an algorithm which contained 5 steps;

1. The optimisation started by dividing the design task into sub-tasks.

2. A number of alternatives had to be generated for each sub-task.

3. Omitting any solutions, which were inflexible, impractical, or infeasible, based on criteria such as friction level, friction stability, stiffness, toughness, and strength.

4. Attribute-based utility values were calculated. This was achieved by choosing design attributes.

5. Then, weights were assigned to the attributes. The next step was to compare the attributes with each other in order to determine rating values of the attributes. The last step was the formulation of objective function and constraints to reach optimal design.

Thurston and Carnahan (1993) developed an intelligent evaluation system to select the best alternative. They evaluated two materials for a bumper beam and identified the criteria to be weight, cost, shape restriction, stiffness and corrosion resistance. Manufacturing cost considerations were included in the knowledge-base system at the early stage of design process to evaluate alternatives concurrently in terms of Concurrent Engineering goals: low cost, high quality, and less lead time.

Das et al. (1995) discussed methodologies for reducing set-up costs for machined parts. This approach was also based on the analysis of machining form features.

Jha (1992) developed a mathematical cost estimation modelling for uncertain and high-tech industrial environment. This methodology focused on estimating the probable cost range and calculating expected cost. In addition, it estimated the cost of some manufacturing processes such as hole making process by injection moulding.

Park and Khoshnevis (1993) presented a new CAPP system for concurrent design of prismatic parts and processes. The hybrid system comprised of a knowledge base expert system and a cost optimisation module. It selected suitable machines for each feature, optimum machining parameters for each candidate process and optimised machining process sequences. Machine set-up time, tooling cost, and process time were calculated based on machinability formula and empirical data. The process planning and cost estimation feedback were also generated.

Taiber (1994) classified manufacturing cost optimisation of prismatic parts as follows:

- Tool cost
- Machine tool cost
- Net machining time
- Non-cutting tool paths
- Number of tool changes.

This approach provided an effective cost calculation and optimisation of mechanical parts using traditional machining techniques such as milling and drilling.
Knowledge-based systems for process planning, and cost estimation of a hole making process can be found in Luong and Spedding, 1995.

Ping et al. (1996) developed a multi-agent system for cost estimation. They stressed that the existing cost estimation methods have two problems:

1. They were incapable of specifying a cost estimation process for complex parts, and
2. They did not give any idea of the uncertainty at an early stage of the design process.

In this system, each agent represented a kind of cost estimation method. The system used a fuzzy classification of cost estimation methods. It included a dynamic optimisation structure to provide the agent with knowledge from the past. The system classified user requirements, made the expert agents execute the design tasks. The model was based on an integrative system and blackboard system. It used a combination of these two paradigms to reduce communication cost, and minimises disadvantages in information exchange bottleneck between agents.

A feature-based manufacturing cost estimation approach has been developed by Fen et al. (1996). Their system focused on machining form features such as holes, slots, flat surfaces, and chamfers. Manufacturing operations and time (cost) related to the manufacturing form features were represented in the system.
In the model, the problem of cost evaluation was formulated to find the shortest path for machining activities such as processes and set-ups. Manufacturing processes for the part were optimised and based on the activity-based approach, in order to reach the optimum solution by assigning unit manufacturing cost to each activity.

Crow (1997) presented an approach to product target cost. It consisted of three premises:

1. making products affordable for customers,
2. while defining product requirements, its cost was treated as an independent variable,
3. working to reach target product cost during product and process development.

Ou-Yang and Lin (1997) presented an integrated framework for early manufacturing cost estimation. They stressed that researchers had given little attention to manufacturing cost estimation in the early design stages. The proposed model was based on the feature-based approach in that, manufacturing form features were the key element in estimating manufacturing cost. The model comprised a CAD/CAM system, an analysis module and a reference module.
The designer retrieved form features from the CAD/CAM system to construct the part. The system then carried out manufacturability analysis, process selection and time-cost estimation. However, the system had limitations. Firstly, alternative processes for the form features were not considered.
Also, some of the features, that required more than one process due to tolerances and surface finishes, had not been considered. Secondly, the validity of the analysed results was questionable.

Skalak et al. (1998) presented a technique for constraint optimisation problems based on the genetic algorithm. They stressed that there were two approaches for handling design solutions subject to the defined constraints. These approaches were classified as follows:

1. Leaving out solutions that were not feasible,
2. Assigning penalties for lack of feasibility.

The first approach could be applied effectively to certain specific problems. However, the algorithm would spend significant amount of time seeking out a few solutions that did not violate the constraints.
The latter was an unconstrained optimisation problem. However, the algorithm had to be re-run many times in order to eliminate non valid solutions, and find a feasible one.
Fuzzy logic based intelligent systems have been developed for the selection of cutting parameters in machining operations (Hashmi et al. (1998)), and the computerisation process of machining information included in machining handbooks (ElBaradie, (1997)).

Tappeta and Renaud (1997) introduced a methodology for concurrent design optimisation of structural design problems (SAND). It was based on constraints and their impact on algorithm efficiency. The SAND approach provided concurrency between various life-cycle issues during the design process.

Other research work on product and process design optimisation can be found in Palmer and Hall, 1992; Wujek et al., 1996; and Seif, 1998.

Bullinger et al. (1998) described approaches to life-cycle cost estimation of a product designed in a Concurrent Engineering environment. Life cycle cost (LCC) aims to find out cost drivers and causes for various cost components during the product life cycle as well as to stimulate their contribution. This lead to a reduction in life cycle cost, energy consumption in production, and material.

LCC helped to consider the real cost of a product for industries where all environmental and product's life cycle cost had not been considered. There are tools for supporting LCC such as Life-cycle Assembly, Service and Recycling (LASeR), developed at Ohio State University and Stanford University, ReStar (Recycling Star, developed at Carnegie Mellon University), and RECYCLEAN (an information system for environmental staff and a training tool for designers).

Asiedu and Gu (1998) stated that although there were methodologies that have proven to be successful in cost reduction, the criteria for design evaluation of these methodologies was not cost. Therefore, methodologies and tools were required to directly provide cost information to designers. They suggested that a framework for life cycle cost analysis could provide designers with the estimated total product cost from development to disposability.

Gayretli and Abdalla (1998) developed a knowledge-based system using a constraint-based model and manufacturing form features in order to help designers to create real-time cost estimation and feasible process plans. The system enabled designers to define and modify constraints such as process cost and the time required to reach a number of processes that satisfy the requirements. In addition, it helped compare possible processes to each other, in order to determine feasible process combinations. The manufacturing cost was determined by the calculation of the process cost of each feature. The cost model and algorithm for the estimation and optimisation of manufacturing processes were also presented. This methodology was a useful tool, which could be extended to cover other process constraints and user requirements.

Cost optimisation was defined as minimising the total process time and cost which were subject to cutting speed, feed-rate, cutting force, power, and surface finish constraints (Chang and Wysk, 1985).

Manufacturability analysis was very important in order to reduce the cost of products. Thus, the cost estimation and optimisation of a design had to be determined after a detailed manufacturability analysis. Methodologies for manufacturability analysis of mechanical components had been developed to reduce the product cost (Shah et al., 1990 and Feng and Kusiak, 1995).

Marri et al (1999) pointed out that most of the existing CAPP systems had limited cost estimation capability. They also suggested that a CAPP system should offer an integrated facility for process planning and time/cost estimation in order to help medium sized manufacturing companies.

2.7 Computer-Aided Process Planning (CAPP)

Process planning defined, as the systematic consideration of the detailed methods which components, can be produced from raw material to finished product. CAPP was the major element in computer aided manufacturing (CIM) (Marri et al., 1998). The main goal in process planning was to produce products in accordance with the specification to achieve the highest possible quality. However, economic considerations were also very important. Producing an optimal process plan was very desirable and then improving it with respect to some given criteria (Palmer et al., 1992). Process optimisation could be carried out at several detail levels. At the highest level, it is necessary to choose processes, machine tools, and sequencing of operations. At a more detailed level, there was the optimisation of cutting parameters such as feed-rate, cutting speed and depth of cut. In addition, estimation of process time and cost of processes, tools and set-ups were included at this level. Computer Aided Process Planning (CAPP) eliminated most of the decisions on process planning and provided a consistent plan to achieve company aims. It also helped to reduce the demands on the skilled process planner, planning time, and manufacturing cost, and enabled the creation of process plans consistently and accurately, and increased productivity.

Although, many CAPP systems have been developed, they were not effective enough as far as constraints of machining operations (i.e. tolerance, surface finish, feed rate), cost estimation capability, minimisation of manufacturing time and cost, optimum use of available manufacturing facilities, and uncertain nature of the shop floor were concerned. For these reasons, many companies had their own research groups to develop their own CAPP systems (Marri et al., 1998).

2.7.1 Variant Process Planning

This approach was one of the earliest attempts to computerise process-planning techniques. In this model, similar parts had similar process plans. In order to identify similarities between process plans, computers were used to retrieve, from the system, the plans that match requirements for a specific part. Coding and classifying parts were carried out using GT-based coding and a classification model.

This process planning approach was good enough to improve the existing process planning and was easy to use. However, the limitation of components to be planned was a disadvantage, and details of process plans could not be generated.

2.7.2 Generative Process Planning

This model is defined as a system synthesising a process plan for a new part. Information about the generation of process plans is stored in a manufacturing database. Therefore, details of a plan are available in the database. Using this model, operations required, machine and operation sequences are generated automatically. Other process functions such as machine selection, process optimisation, tool selection are also generated via the generative planning technique. Consistency in process planning is achieved by this approach. In order to execute this approach successfully and effectively, it is necessary to identify the logic of process planning, and define the component to be manufactured clearly and precisely in a computer language format, and incorporate the logic of process planning and component description into an integrated manufacturing database. Some popular methods for describing components in this model are codes, special descriptive language, CAD models, and methods for representing logic of process planning are shown as follows:

- Decision trees

- Decision tables
- Artificial intelligence-based approaches
- Knowledge representation

Zhou et al. (1995) developed a CAPP system (U-CAPP) for the flexibility of the CAPP system and the integration purposes. The system was user-oriented, and used an event-driven architecture and knowledge frames in manufacturing process planning. It was based on the feature-based technique, and suitable for machining process planning of prismatic parts. The procedure of the generative process planning approach was complex, and no complete generative process planning system was available up to now (Chang, 1990).

Lee et al. (1991) presented an intelligent knowledge-based object-oriented process planning system for the manufacture of progressive dies (IKOOPPS). The system included a feature recognition module. Manufacturing form features were used to carry out process planning. Design and manufacturing knowledge were represented as rules, objects and procedures in the system. The system was limited to progressive die plates.

Duda and Pobozniak (1995) developed a rule-based expert system for process planning. In this system process planning knowledge was represented as rules with a control mechanism. Based on the knowledge three stages were specified: selection of the generalised manufacturing process, design of the semi finished part and generation of the machining processes.

Research work with more emphasis on the integration of job-shop scheduling and process planning by using Petri net models can be found in Kiritris et al. (1994) and Horvath and Rudas (1994). Recently, some research work has been carried out by using feature-based modelling and neural network-based techniques such that by Devireddy and Ghosh (1999).

2.8 Expert Systems

2.8.1 Definition

Expert systems are computer programs, which emulate human experts within a specific domain (Olson and Courtney (1992)). It includes artificial intelligence in which computers can be programmed to emulate human thinking. Expert systems have the ability to apply expert knowledge in order to solve problem from a specific problem area. The main aim of the expert system is to seek to develop the factors experts use in dealing with a problem and reach the same conclusions experts would have reached themselves. They provide a way to store valuable, but perishable expertise. For these reasons, expert systems have widely been developed and used for many applications such as machining data selection in the manufacturing industry (ElBaradie (1997), and Hashmi et al. (1997)).

2.8.2 Architecture of Expert Systems

An expert system usually consists of three major elements; user interface, inference engine and knowledge base. The user interface is the means by which a user can access the expert system. It includes interactive answers, explanations and menus. The inference engine is the element, which scans facts and rules from the information stored in the knowledge base system. It provides answers to queries given by the system user, and has the ability to look through the knowledge base system, and apply the rules in order to solve a particular problem (Smith (1990)). The most common means of inference engines are forward chaining, backward chaining, and object-oriented programming. The knowledge base includes a series of facts and rules associated with a particular problem domain. These facts and rules are represented in an appropriate programming language such as LISP and C++, and knowledge representation techniques such as production rules, frames, and object-oriented programming (OOP).

2.8.3 Knowledge Representation Techniques

Knowledge can be represented in different format using various techniques such as constraints, frames, production rules, and object-oriented programming.

2.8.3.1 Constraints

A design variable can be stored in a slot of a unit in the knowledge base system. The value of a slot can be kept within certain limits as constraints. Constraints are a very effective way of holding variables in a slot or a rule class, because any new value entered in the system has to be checked against the specified limits.

2.8.3.2 Frames

A frame is described as a structure for storing interconnected information about a design and an object. It is a very effective means of knowledge representation of objects and object classes (Zhou et al. (1995)). A frame consists of a name and a number of slots. The value of slots could be numeric (12, 24), logical (yes or no), procedural (methods) and symbolic (e.g. steel).

The frames also allowed designers to attach images and active values to any slots in order to monitor value changes. By using facets, values of slots could be controlled.

2.8.3.3 Production Rules

Production rules are the most commonly used knowledge representation technique. The rules are defined in the form of forward-chaining or backward chaining. The production rules are used to establish design and manufacturing constraints as rules.

The form of production rules is:

IF (condition) **THEN** (action).

The advantage of production rules is the flexibility of changing the knowledge bases (Lee et al. (1991)).

2.8.3.4 Object-Oriented Programming(OOP)

Object-oriented programming is a methodology, which model real world concepts as objects, that groups collections of data together by the similarities in their structure and behaviour (Sun Common Lisp 4.0 Object System, 1990). This provides a very effective and most efficient way of organising design and manufacturing objects into various classes (Lee et al. (1991)). The object-oriented approach aims to integrate data structure and functional behaviour through modelling objects (Zhang and Zhang (1997)).

2.8.4 Reasoning Methods

When a model of an application domain is built, descriptive information is mainly used. However, the model should contain problem solving techniques and reasoning heuristics.

Objects in knowledge bases can carry problem-solving behaviour in the form of methods stored in slots inside the objects. Behaviour or a function can be localised inside objects in knowledge bases.

The function includes inside objects, which execute a given task such as calculations. Methods are very flexible and can be activated in rule classes by using special commands.

Production rules can be used for reasoning. Rule classes are connected to each other, namely the conclusion of one rule is included in the premise of another rule. This is called chaining. When chaining starts the conclusions of one rule class match premises of another rule class. Chaining is used either in a forward or backward direction.

Forward chaining tries to find the implications of new information. It generally starts from the input of new data. Therefore, it is called event-driven or data driven reasoning. The system scans the rules whose premises include the new fact. As the backward chaining starts with the goal of proving something, it is called goal-driven. The system scans the rules whose conclusions match the fact to be verified. These reasoning systems can be integrated into rule classes to create more powerful rule application and make the system run more efficiently.

2.9 Design Consistency in Concurrent Engineering

Prasad et al. (1992) stated that product development in large production companies needs the involvement of a number of engineers from different departments. Conflicts sometime existed in the objectives of different departments. This necessitated the critical consideration of several tasks such as overall co-ordination, control, consistency, and data integrity. They presented a concept of design schemata in order to support Concurrent Engineering from an enterprise perspective.

Their approach focused on the use of the existing information and negotiation of conflicts that arose from design inconsistencies. In addition, a data dictionary for the conceptual centralisation of design information was proposed. CE requirements for information management were classified as follows: information modelling, teaming and sharing, planning and scheduling, networking and distribution, reasoning and negotiation, collaborative decision making, and organisation and management.

Yoshimura and Yoshikawa (1998) stressed that the acquisition of new knowledge and sharing information between separate groups of designers are the key factors essential for co-operative product design. They suggested that knowledge sharing among designers or enterprises consisting of individuals, who have different knowledge based on their experience, was a very beneficial strategy for achieving advanced product design solutions.

D'Ambrosia et al. (1996) developed a decision-making methodology called hierarchical CE that included a general decision-making methodology and agent architecture for solving hierarchical CE problems. This approach was based on the distribution of the preferences and constraints from a supervisor agent to sub-agents, who utilised their local expertise within this global context provided by this global information.

The system agent formulated a problem and defined design variables and their associated constraints. These were inherited to all the sub-agents. The sub-agents, with local expertise, could apply their preferences and constraints if they did not violate the supervisor agent constraints and preferences.

Agents tried to solve a problem by satisfying the supervisor agent and their local constraints to reach the best solution. A consistency violation existed if any variable assignments violate constraints.

The constraint agent directed the sub-agents to change previous assignments to eliminate the constraint violations. When consistency violation was absent, in the constraint network, any possible assignment of variables lead to a feasible design. However, they suggested that the optimal solution for a hierarchical organisation of agents had firmly to be defined, to achieve overall co-ordination between agents. In addition, any changes in a design variable required extensive communication between agents, hence longer time to reach the optimum solution.

Peter et al. (1991) presented an approach to concurrent engineering using artificial intelligence constraints network, which could help a designer to improve a design. The intelligent constraint network had a number of advantages:

1. flexibility to allow the design problem to be analysed from different points of view.

2. providing designers with the design of products with incomplete information.

3. ability to handle large variety of life-cycle information.

The proposed approach, called Larry, helped the designer to improve the life-cycle effectiveness of the product. As the model addressed the problem of hole drilling in printed circuit boards, the design variables were linked to the constraints.

It used a constraint network language called SPARK. The developed system had the ability to handle a wide variety of variables and constraint types, domain independence and to explain its reasoning to the user. If Larry detected any constraint violation, notification was given to the designer.

Bowen (1997) introduced a methodology for decision-making activities between members of a product development team in a consistent manner. The methodology focused on the question of how, when team members made consistent decisions, suggestions could be given in order to achieve consistency.

A constraint-based approach, including dependency records for design co-ordination, was implemented. In this model, design variables had their own constraints. When any constraints were violated, the design team were advised of the allowable values of the variables.

Noble (1993) presented a conceptual framework for design consistency problems. Design consistency necessitated effective and timely communication between different design functions. One aspect of this communication was design decision consistency. This integrated different design areas through communication, within an organisation, in a consistent manner. The model used rule-based system for a specific company's design project to solve the above problems. He stressed that there are three issues related to design consistency:

- constraints,
- information,
- integration.

The constraint-based concurrent engineering approach defined a set of constraints associated to the various product life-cycle issues. Satisfaction of these constraints was the key to reach a successful design in this approach. However, pure constraint satisfaction could be inappropriate and not feasible because of the complexity of the issues and problems associated with concurrent engineering.
To solve this problem constraint programming languages have been advanced to represent constraint networks to consider life-cycle-engineering issues. The availability of concurrent information is another issue associated with design consistency.

Inefficient information flow was the first issue associated with the integration of design with manufacturing. Heterogeneous design database and blackboard system could be a solution to this problem. The majority of the research into concurrent engineering has focused on integrated product and process design issues. However, the scope of integration should cover all the product life-cycle issues so that design decisions are totally consistent with the overall objectives of an organisation.

The proposed approach comprised of five design functions: management, finance/accounting, marketing, production engineering and product engineering. The design consistency concept required the participation of a representative from each design function that had input to the design process. The design consistency approach aimed to provide an environment where design information from different design areas within an organisation could interact and affect other departments. The result of this process was to show what design information is consistent with other departments, and which was conflicting with that specified by another department.
As the approach was a rule-based system, it had advantages and disadvantages. It was easy to explain design requirements in terms of rules. However, it could become very complex when covering all various design interactions.

Pena-Mora et al. (1994) presented a framework called SHARED-DRIMS for resolving conflicts within an organisation where many different types of professionals, who must interact and communicate with one another.
The proposed approach included mechanisms for checking interactions and prompting hypotheses about the reasons for the interaction. The system used three strategies to resolve conflicts.
Firstly, it might use heuristic rules for common conflicts. Secondly, it might search through past designs for conflict resolution. Thirdly, the system could provide information for the designer to resolve the conflict. If a conflict could not be resolved by the first two strategies, the third case is applied. In order to resolve conflicts the system provided designers with recommendations and the results of any changes of values.

This model had two advantages. Firstly, it provided representation of design knowledge in terms of the reasoning process, which was used by designer to design a product that satisfied the requirements. Also, it provided active communication support for different collaborating participants. Secondly, the model provided computer support for conflict resolution. It could solve known conflicts when available solutions were present in the knowledge base.

However, the system needed to be tested in a real working environment where there were organisational constraints and time pressures. Also, the user-friendliness of the system needed to be explored. The applicability of the system to industry was questionable.

Hayes and Sun (1994) developed a system, which included a suggestion generator and manufacturing planner, P^3, which analysed a design and generated a manufacturing constraint network. Decisions on design, mainly dimensions and tolerances, were checked by the system to prevent inconsistencies with manufacturing constraints defined by manufacturing planners. The suggestion generator gave advice on the design by analysing the manufacturing constraint network. The system suggestions were fed back to the designer who decided whether or not to accept and make the necessary changes. The system was limited to cover other life-cycle issues of products.

Harrington et al. (1995) addressed the issues and key variables in conflict resolution and presented a strategy for managing the conflict resolution process to support concurrent engineering. Conflict was defined as "disagreement between two or more view points on some decision or value proposed in a design". The aim of concurrent engineering was to share life-cycle perspectives and goals in the early stages of the design process, to avoid conflicts during the design session. They proposed negotiation, as a tool for analysing conflicts, applying an appropriate strategy, and observing its performance.
The proposed approach was a knowledge-base negotiation strategy that included five steps:

- identification of conflict

- search for cause of the conflict
- analysing conflict situation
- selection of conflict resolution strategy
- applying conflict resolution strategy

They stressed that there was no particular strategy that could be applied to all conflict situations. The selection of a strategy was not a simple process, and there might be a situation where the user had to solve conflicts. When a solution was found there was also the problem of the optimality of the solution. Conflict resolution required a good understanding of the problem and a suitable selection of a resolution strategy to eliminate it.

Susan et al. (1996) presented blackboard architecture for supporting the integration of heterogeneous collaborative agents. The blackboard architecture comprised of three major elements: the blackboard database, control mechanism and a set of experts. As information management of concurrent engineering was a major problem, the developed blackboard database system provided efficient global information management. It included any type of shared information needed in different design functions such as design specification, and process planning.

More detailed research work on information management for concurrent engineering can be found in Eversheimn et al., 1997; Gadient et al., 1997; and Prasad et al., 1993.

Balasubramanyam and Norrie (1996) developed a multi-agent system for concurrent design, process planning, routing and production scheduling. The system included a feature-based design system for prismatic components, a shop-floor system to represent available manufacturing facilities, a control interface responsible for management of the available manufacturing resources. In this system, different design, domain information and responsibilities were represented by individual intelligent agents who had the necessary knowledge for evaluating much of the life-cycle information of the product. The designer generated parts by using a pre-processed blank geometry.

Each agent checked features and their parameters, such as dimensions and tolerances, to see if they were to be consistent with the available manufacturing resources. The results of analysis and suggestions were reported to the designer by a user interface.

Gayretli and Abdalla (1999) introduced a consistency management system that was responsible for the management of the decision-making process and which dealt with conflict situations and justification of decisions made on design. The system detected conflicts arising from different life-cycle perspectives, gave warnings and explanations to the users and finally applied a suitable strategy for solving conflicts in order to ensure design consistency in the constraint network and design output. The system also allowed designers to solve and monitor design violations via the user interface.

2.10 Summary of the Previous Research Work

This chapter presented a critical analysis of previous research work in major areas related to this research in detail. In the area of Concurrent Engineering it was pointed out that the CE approach requires the early considerations and involvement of various activities associated with design and manufacturing in parallel rather than sequential. Despite the presence of many tools, techniques, and methodologies developed for supporting CE, to achieve the above aims, the potential of CE has not yet been fully exploited. There are indications that the success of CE approach was based on well-founded methods, effective tools, and a dedicated team.

Advanced manufacturing technologies will be costly to implement for the manufacturers. No single company has all the necessary expertise. Therefore, manufacturers and institutions have been undertaking co-operative technology development in order to share risks, cost and expertise. International co-operation and management is thus very important.

The use of enterprise integration (EI) methodologies and tools in manufacturing companies has helped to improve their business competitiveness in many ways such as shorter lead-time, higher product quality and reliability, less waste and lower product cost.

Representation of information associated with various product life-cycle issues was very important for effective use during the design process to accomplish many tasks such as manufacturability analysis, process selection and process time and cost estimation. A constraint-based system was a useful tool that was used to model and handle design requirements. However, complex designs could not be easily represented in terms of constraints and variables. The system should also offer flexibility to enable designers to attach new databases to the system. In addition, it must be integrated with an information management system for avoiding from design conflicts.

Techniques such as Value Engineering, QFD, FMEA and Taguchi have to be used in the design process to ensure a product design to meet customer requirements. However, most systems for supporting CE still lack of the use of these techniques.

In the areas of feature-based systems for process selection and evaluation, previous research work has focused on form features, which are the key to selection and evaluation of manufacturing processes. A number of process plans were assigned to the part, and each plan was evaluated by using some criteria.

A literature review, in the area of process time-cost estimation and optimisation, showed that the systems for supporting CE have to provide designers with process time-cost estimation at the early stages of the design process, to ensure a product design consistent with the design requirements.

Marri et al., (1999) emphasised that most of the existing CAPP systems have limited functions for time/cost estimation capability. It was also suggested that a CAPP system had to offer an integrated facility for process planning and time/cost estimation in order to help medium sized companies.

Existing manufacturing capabilities have to be taken into account, in order to ensure manufacturability of the product within the available manufacturing facilities. However, researchers have given little attention to manufacturing cost estimation in the early stages of the design process (Ou-Yang and Lin (1997)). Recent research work has concentrated on optimisation of manufacturing processes as it plays an important role in cost reduction. There were mainly three main approaches for process optimisation; weighted objective approach, constraint optimisation based on genetic algorithm and activity-based approach. Asiedu and Gu (1998) stressed that methodologies and tools for concurrent engineering are needed to provide cost information directly to the designers.

Review, in the area of design consistency in concurrent engineering, showed that concurrent product and process development required the involvement of a number of engineers from different departments. One of the most important issues in CE was to provide effective and timely communication within different design areas. This needed the critical consideration of various tasks such as overall co-ordination, control, consistency, and data integrity to avoid conflicts arising from different domains.

This could be achieved through the integration of different design areas by consistent communication in an organisation. Such integration had to include a strategy for conflict resolution in order to avoid disagreements within the different areas. Manufacturing systems were complex entities, which included people, products, processes, information systems and various data, and storage systems. This complexity required systems to be modelled by the use of a variety of views and modelling formalisms. The state-of-the-art computer-based tools such as virtual reality and World Wide Web (WWW) should be used to visualise, manipulate and interact with manufacturing systems and complex data via network systems. Virtual reality environments have been used in industries for realistic simulation of new manufacturing processes before they were tried on the factory floor.

Although, tools for supporting design consistency have been developed, such as blackboard systems, multi-agent systems, constraint-based systems and rule-based systems but they all had limitations.

Firstly, they were not capable of covering all product life-cycle interactions. Secondly, these systems became complex and time-consuming when the information flow increases.

Many attempts have been made to describe a clear model for the accomplishment of concurrent product and process design. However, most of these existing approaches had not fully addressed the problem of the integration of design with manufacture and they had limitations as far as design optimisation, early process cost-time estimation, design consistency, limited product features and user interface facilities were concerned.

The current research work proposes a novel concurrent engineering approach addressing these problems. It will allow sharing of information within a team, including effective representation of product design and manufacturing facilities and decision-making activities in a systematic and consistent manner.

The proposed system will also enable the designer to access to databases, and monitor constraints violations via a user-friendly interface, and control the different operational modules of the system, and resolve conflicts at run-time, and change constraints.

CHAPTER 3

3 THE PROPOSED CONCURRENT PRODUCT AND PROCESS DESIGN APPROACH

3.1 Overview

This chapter describes the developed methodology for supporting concurrent product and process design. As discussed in the literature review, most of these existing approaches to concurrent engineering had not fully addressed the problem of the integration of design with manufacture. They also had limitations as far as design optimisation, early process cost-time estimation, design consistency, limited product features and user interface facilities were concerned. Developing an intelligent design system is proposed which will accomplish this integration for a concurrent product development strategy.

3.2 Introduction

Concurrent engineering is a systematic approach to the integrated, concurrent development of a product and its related processes in order to meet customer requirements. Therefore, it is necessary to achieve the concurrent involvement of various life-cycle perspectives into the product development process. This needs an environment where decision making proceeds with large amounts of parallel working. Concurrent engineering requires the inclusion of team values of co-operation, trust, and information sharing to achieve such concurrency. A multidisciplinary team, supported by computer-based tools has to be assembled to achieve the aims of concurrent engineering. Different information from different departments of an organisation should be available and well represented in an efficient way allowing the design team to look into the design from various perspectives.

As there is a variety of information involved in the design process, there is need for an effective information management system to provide the design team with effective and timely communication during the design process. This means that the design team must receive the right information at the right time and at the same time conflicts within the design team must be avoided. In order to avoid disagreements within the team, a conflict resolution strategy must be developed. It must provide the designer with feedback on design violations, decisions made on the design, justifications of the decisions, and explanations of the actions that need to be taken.

Constraint-based systems are tools for the management of life-cycle information. These ensure that the design output is consistent with the design specification, and at the same time prevent design conflicts. Many constraints associated with part features, feature-process relations, machine tools, cutting tools, cost and time must be incorporated into the design process. Given these constraints, cost-effective product designs can be achieved in the early stages of design phase. Representing these constraints in efficient format is very important to evaluate and optimise design effectively, and prevent the designer from time-consuming iterations. Manufacturing process optimisation is another area in which concurrent engineering has placed a great emphasis through its major effect on the product cost. Product features have a strong effect on the optimisation and automation of manufacturing processes. Features associated with certain processes have to be analysed, to estimate process cost and time, and to carry out the process optimisation by considering a number of processes for each feature. The process optimisation covers the selection of machining processes, cutting tools, machine tools, optimum cutting parameters and prototype testing.

3.3 The Proposed Approach to Concurrent Product and Process Design

The proposed model consists of a CAD solid modelling system, design representation module, consistency manager module, constraint-based system, process optimisation, a manufacturability analysis module and various knowledge sources, user interface.

The architecture of the proposed concurrent product and process design paradigm is shown in Figure 3-1. All these elements interact one with another, subject to the type of information necessary and the user requirements. It provides the designer with flexible access to any level of the design process. An overview of the proposed system including a working scenario is described briefly in the following sections. Further details of the system are discussed in subsequent chapters.

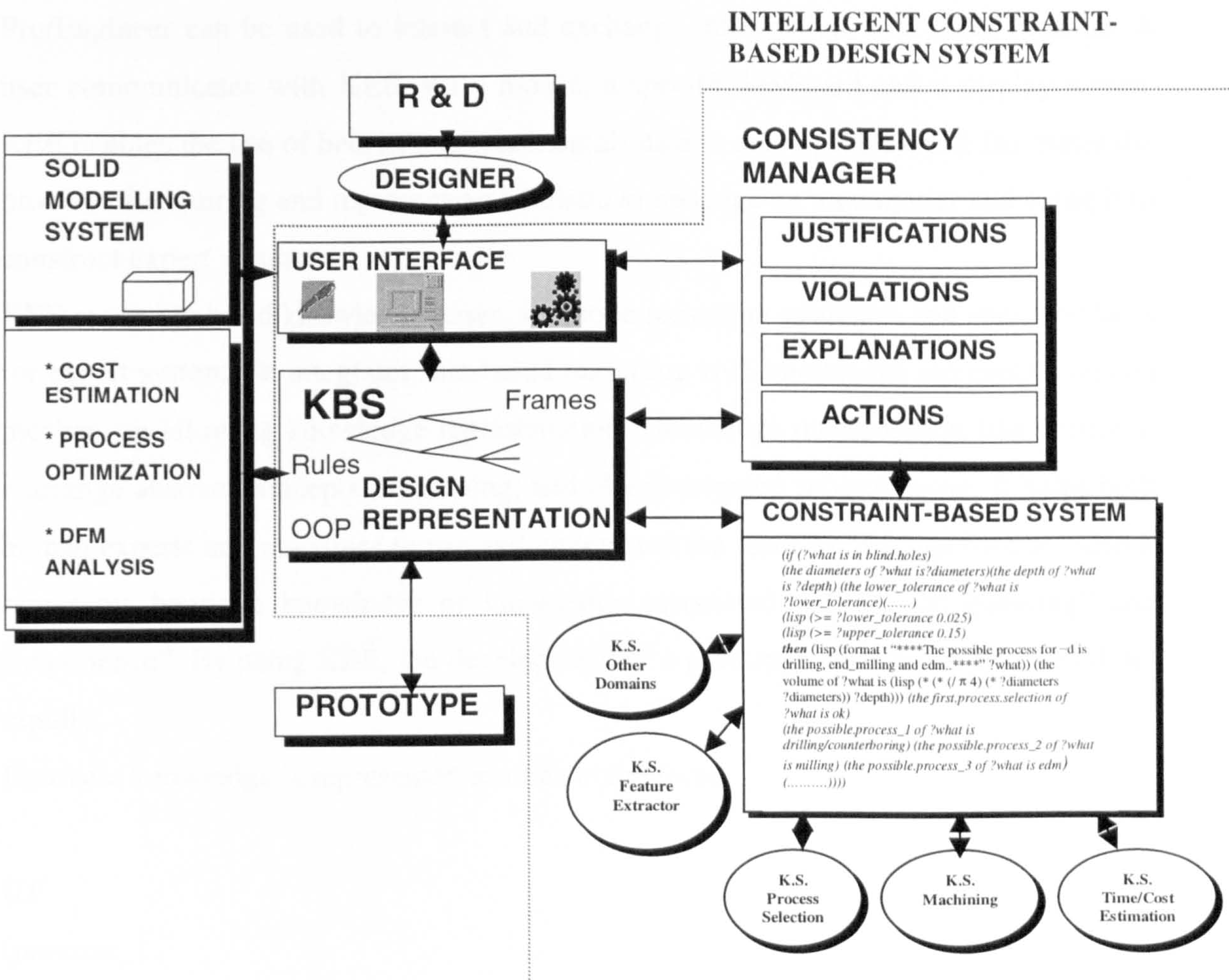


Figure 3-1 The Architecture of the Concurrent Product and Process Design Paradigm

3.4 The Architecture of the Proposed System

3.4.1 Hardware and Software Considerations

The proposed design environment was developed using an expert system toolkit, Knowledge Engineering Environment (KEE), the programming language LISP, and a CAD solid modelling system (Pro/Engineer) run on a Sun Workstation. Pro/Engineer enables the designer to create 3-D solid models. The programmatic interface of Pro/Engineer can be used to interact and exchange information with other systems. A user communicates with KEE, via a mouse, a specific keyboard and a display screen. KEE enables the use of heuristic (experimental) data to solve problems. It facilitates the process of acquiring and representing heuristic knowledge on a computer and using it to construct expert systems.

KEE is used to build knowledge bases, symbolic reasoning strategies and user interfaces for expert systems. It integrates rule-based reasoning with knowledge representation and mechanism allowing knowledge representation, knowledge manipulation (the ability to rearrange abstract concepts), reasoning, and object-oriented programming. It helps both human experts and machines to use and understand the same knowledge format. Also it represents heuristic knowledge or knowledge associated with "good guessing" and "experience". By using KEE, the development of a prototype system can be carried out rapidly.

Heuristic knowledge is represented as rules in the form:

(IF
(premise_1
premise_2
premise_n)
THEN
(conclusion_1
conclusion_2
conclusion_n)).

It accepts rules as a value of unit attributes (slots), and uses method slots to represent procedural knowledge. The method slots are slots whose values are pieces of LISP code. If knowledge bases are organised into a hierarchical family structure, then creating a knowledge base for an expert system becomes a simpler task. In the same way, parents can transmit characteristics to their children, the designer can organise knowledge, represented in units, into such a family structure. Inheritance in KEE allows a tremendous economy in data input. KEE allows users to concentrate their efforts on specifying differences. It also provides ready-made modules such as the rule interpreter and a programming environment to generate specialised representation and reasoning schemes for particular problems. The programming environment in KEE integrates LISP with object-oriented computing, rule-based reasoning and active slots. The user can add new data types as new units to the KEE data type knowledge base. It helps construct expert systems for design analyses, developing a plan or a design and an experiment. It is also used to build a user interface, represent experimental knowledge about design and manufacturing and create design and production rules.

3.4.2 Constraint-Based System Module

The constraint-based system is used to model and handle design requirements. The developed module uses constraints for modelling information on various life-cycle issues, for their effective use during the design process as shown in Figure 3-2. It includes constraints from different design domains, variables from the design model and a constraint propagation module, for ensuring design consistency. In the system, design variables are attached to constraints in order to ensure that values for the variables do not violate those constraints. When the user assigns a value to a variable, the constraints propagation is carried out to check if the assigned value violates any constraints. A valid solution is reached after all constraints are satisfied. In the case of constraint violation, warnings are given to the user with some recommendations, which he/she has to take into consideration.

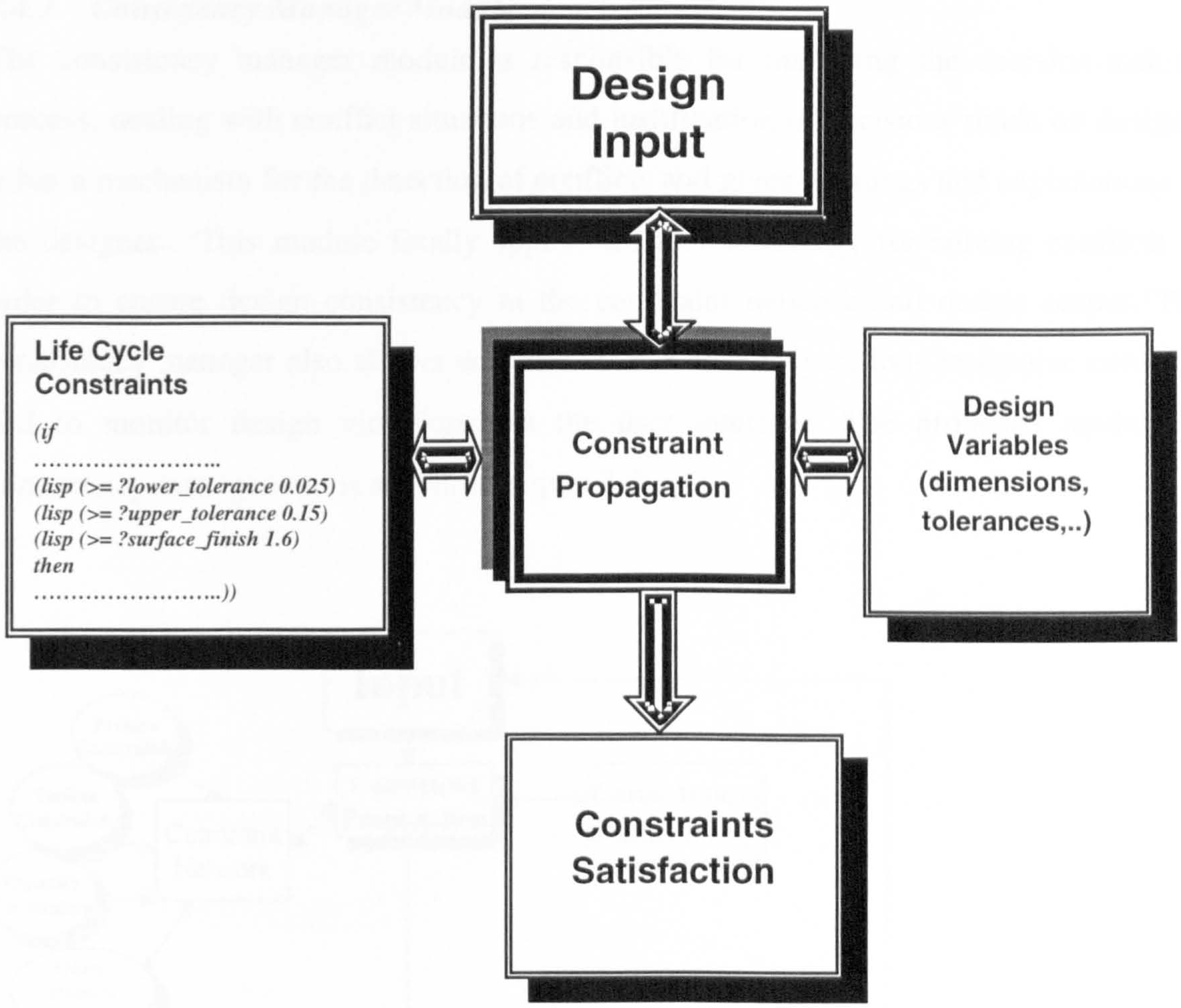


Figure 3-2 The Proposed Constraints-Based Module

Constraints collected from different knowledge sources, such as expert people, can be formulated into rules, variables, values and domain. The proposed module covers most of the aspects of design and manufacture constraints, such as market constraints, process constraints, machine constraints, material constraints, tooling constraints, part constraints, and tolerance and surface finish constraints. The constraint-based system is also linked to the consistency manager module and the design representation module. The consistency manager ensures that there are no-violations in the system, and that there is constraint satisfaction in the design and manufacturing areas.

3.4.3 Consistency Manager Module

The consistency manager module is responsible for managing the decision-making process, dealing with conflict situations and justification of decisions made on designs. It has a mechanism for the detection of conflicts and gives warnings and explanations to the designer. This module finally applies a suitable strategy for solving conflicts in order to ensure design consistency in the constraint network and design output. The consistency manager also allows designer to take necessary actions to resolve conflicts and to monitor design violations via the user interface. The proposed model for consistency management is shown in Figure 3-3.

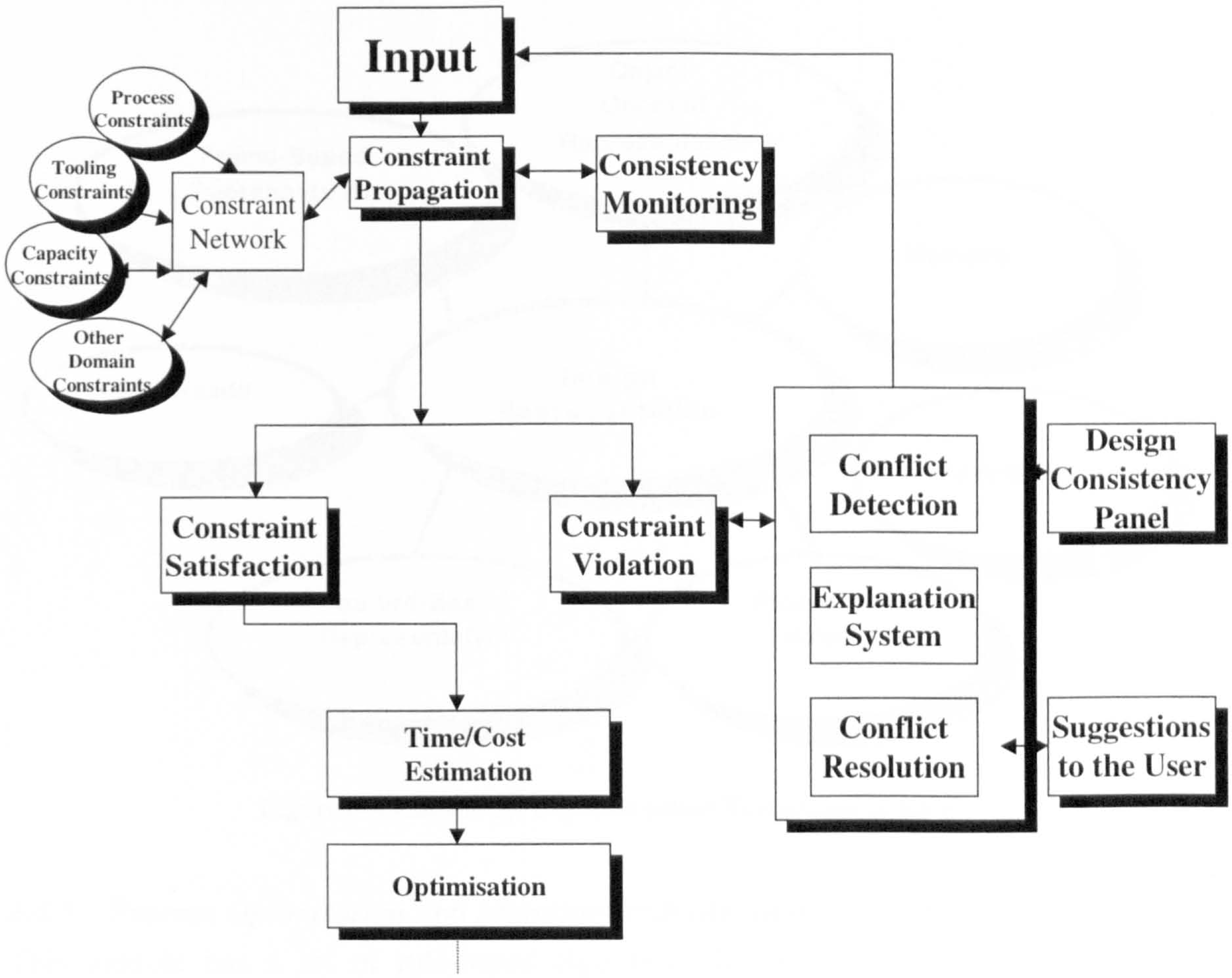


Figure 3-3 The Proposed Model for Consistency Management

3.4.4 Design Representation Module

The knowledge-base system toolkit KEE (Knowledge Engineering Environment developed by Intellicorp.) has been used to represent and model the product life cycle requirements and the design model. Building the design model and its requirements, in a systematic and well-organised way, is essential in order to provide an effective interaction between the various design tasks, such as design and manufacturing. KEE provides various techniques for knowledge representation such as production rules, frames, object-oriented programming via methods and production rules, as shown in Figure 3-4. The flexibility of these techniques enables designers to modify the existing objects or classes, and add new units and attributes.

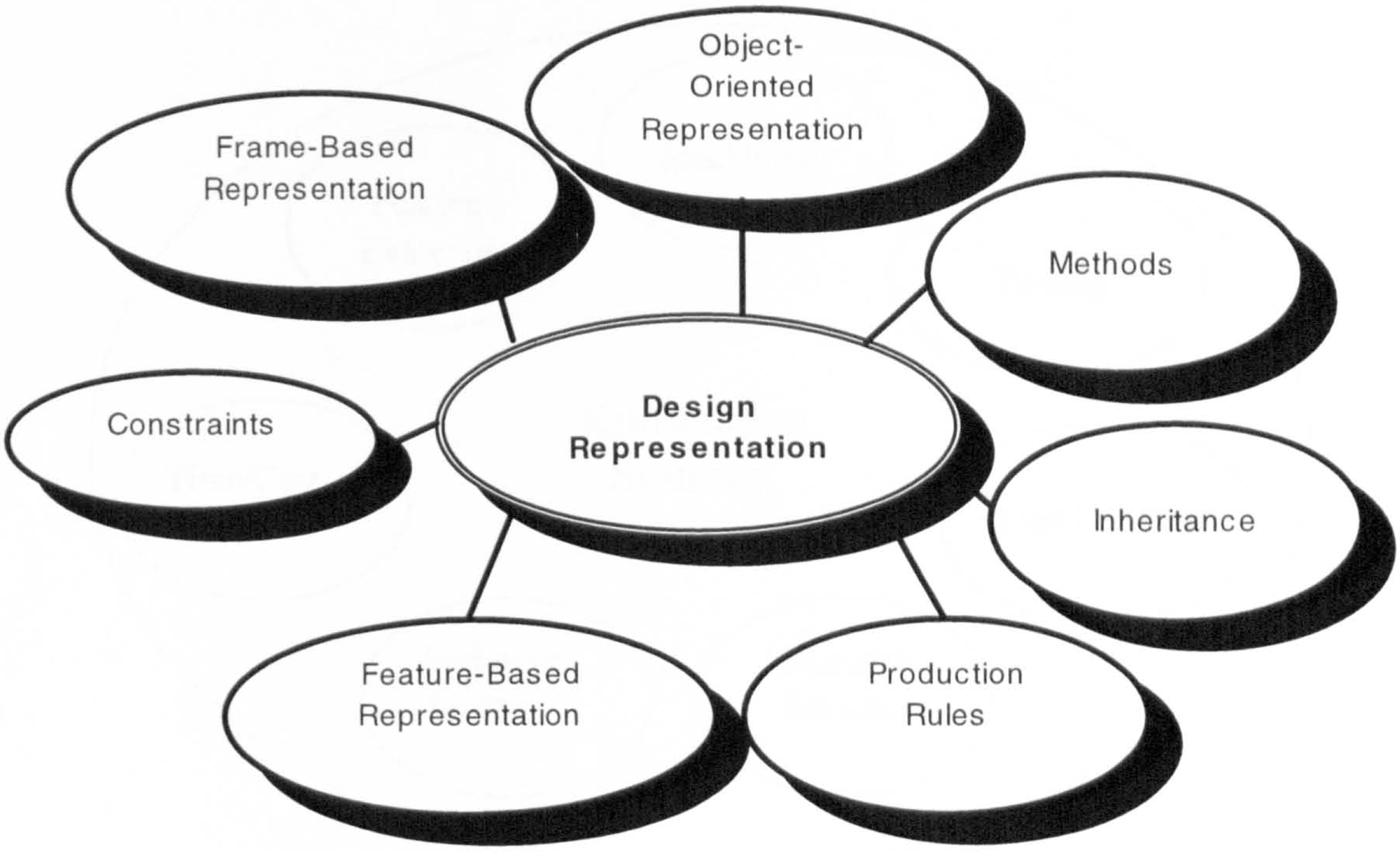


Figure 3-4 Knowledge Representation Techniques in KEE

3.4.5 Process Optimisation and Manufacturability Analysis Module

This module has a set of rule-based algorithms for analysing a component and its features, in order to select most suitable processes, machines and tools. The selected processes are then evaluated using a set of criteria. The process times and costs of the components are estimated in order to ensure the component's manufacturability with the available manufacturing facilities.

The system analyses the processes and calculates the total machining cost of the product including material, tooling, machining, overhead, and labour cost. If the targeted process costs and times are not reached, then the user can interact with the system to modify the design. This process continues until a cost-effective product is obtained. Further details of this module is explained in Chapter 5.

3.4.6 Knowledge Sources

Knowledge sources are collections of requirements represented in the form of constraints from various domains in the product life cycle (Figure 3-5). Those constraints are modelled as sets of constraints in terms of rules, objects, and methods in the system. Conflicts between different domains are resolved by the consistency management system.

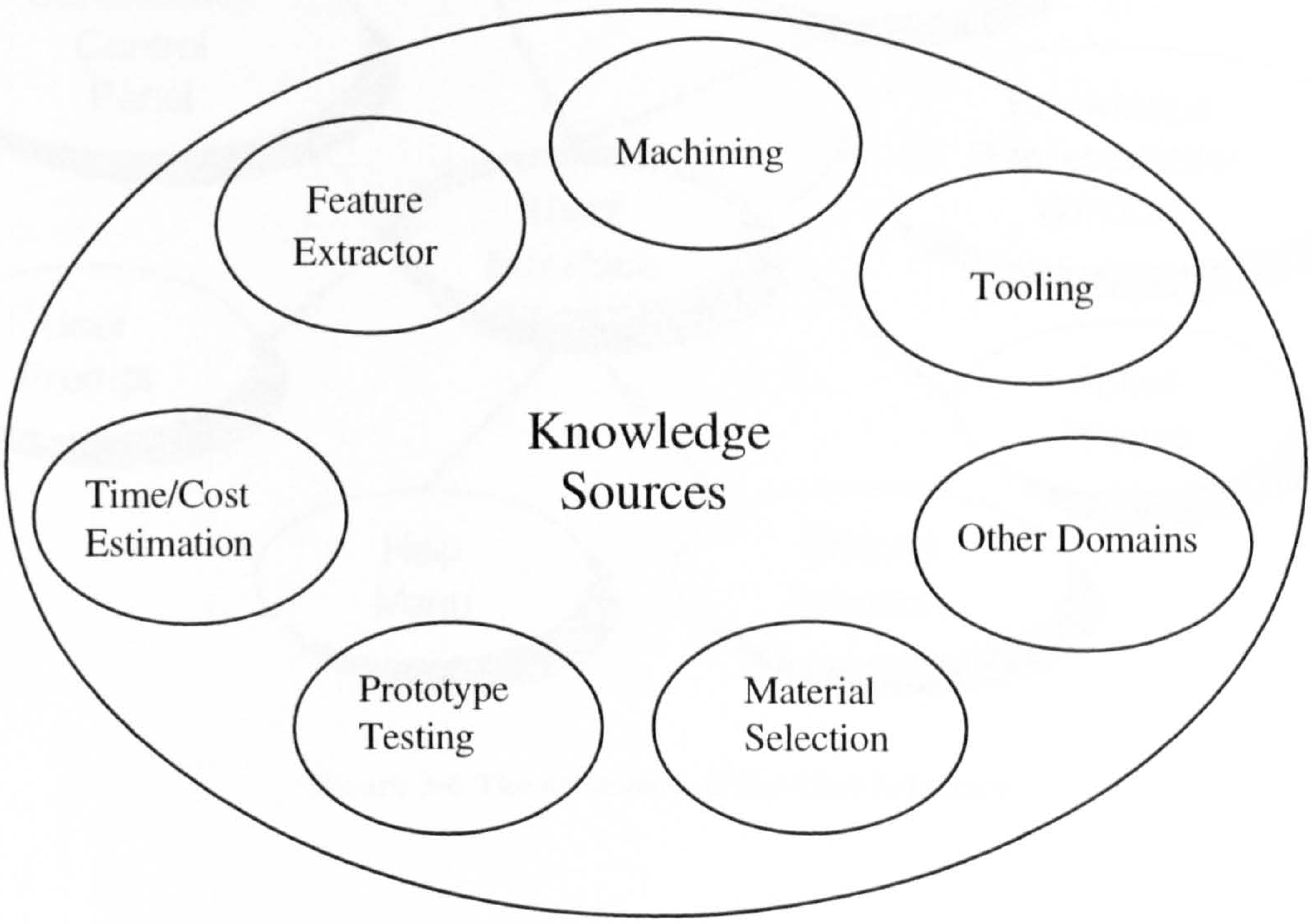


Figure 3-5 Various Knowledge Sources

3.4.7 User Interface Module

To provide the user with an interactive design environment, a user-friendly interface has been developed as an important part of the expert system. This enables the user to use the system easily and efficiently (Figure 3-6). Some of KEE interface features, such as menus and images, were implemented to create the user interface so that user-defined values can be obtained which will accomplish the design tasks.

To enable the user to monitor constraint violations and value changes, active images were also incorporated into the system. Activating methods in slots, by the use of a mouse, was made possible by using the method actuators included in the user interface. In addition, the user interface enables users to interact with the CAD solid modelling system (Pro/Engineer) to generate 3-D solid models, add features, modify features and their attributes. The user communicates with the system using a super panel including menus, active images and method actuators. Results from the system are displayed in the Lisp listener, KEE output window, and typescript window.

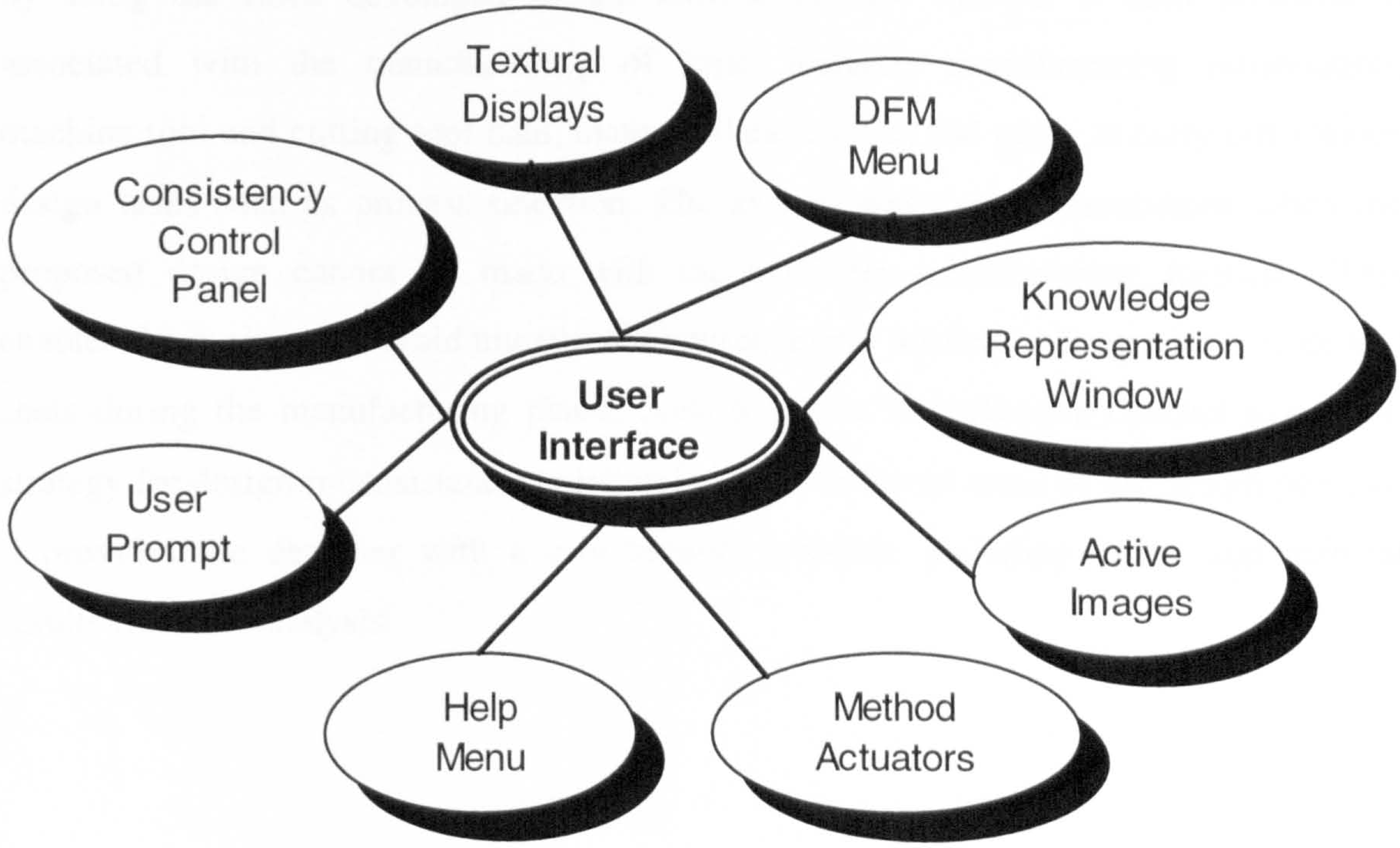


Figure 3-6 The Structure of the User Interface

3.5 A Working Scenario

The procedure for designing a component, via this system, requires that the designer interacts with the CAD system to generate a component and its features. A working scenario of the system is shown in Figure 3-7. The product information obtained from this system is passed to the Knowledge-Base System via the user interface. The KBS includes a number of rules for executing several tasks, constraints and information about various aspects of the design process.

The user enters information, associated with manufacturing resources and capabilities, together with other areas of the design process, into the system as a set of constraints. Based on the information provided from the designer and other expertise, the system carries out various tasks, which are based on satisfaction of the life cycle constraints. It begins by checking the features and dimensions of the component and then the manufacturing facilities and capabilities. It continues with the selection of processes, machines, cutting tools, and then goes on to evaluate, process time and cost. The system provides the designer with an evaluation of all the decisions associated with part design by using the rules developed in the knowledge-base system. It uses information associated with the manufacturing of form features, manufacturing information, machine tool and cutting tool data, material data, criteria and goals to carry out various design tasks such as process selection. The system gives recommendations when the proposed design cannot be made with the available manufacturing facilities. This enables the designer to avoid unexpected consequences leading to longer lead-times and costs during the manufacturing phase. Also it allows the effective conflict resolution strategy for design inconsistencies arising from the different areas of the design process. It provides the designer with a user-friendly interface including visual and textural results from the analysis.

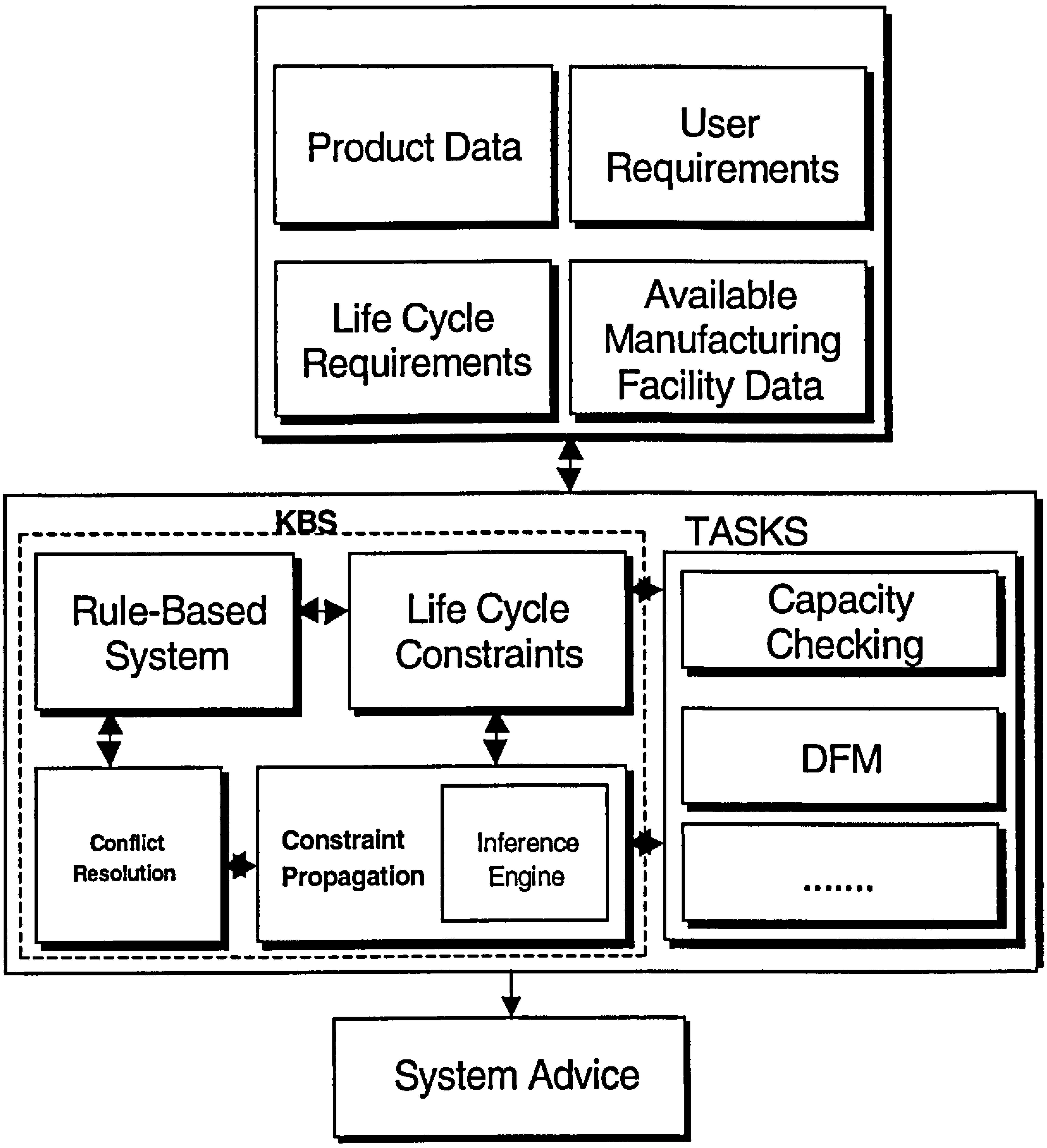


Figure 3-7 A Working Scenario of the System

3.6 A Generic Integrated Constraint-Based Platform for CE

Figure 3-8 illustrates the generic integrated constraint-based platform for concurrent product and process design. It enables designers to consider the issues of the entire product life cycle concurrently in the early design stages. It is made up of a number of elements, which interact with one another. Designers carry out various analyses such as manufacturing capacity checking, process selection and time/cost estimation via the user interface.

He/she has to interact with a CAD system in order to obtain the topological and geometrical attributes of the component so that the analysis process can begin. Design tasks are distributed to individual agents, who have the expert knowledge to accomplish their individual tasks. The agents are linked to a consistency management system and constraint-based system. The consistency management system deals with conflicts amongst the agents. It has the ability to monitor, detect and resolve inconsistencies by proposing solutions to designers. The constraint-based system provides constraint propagation by the constraint network, which is a collection of constraints. Design variables are linked to constraints. When a value is assigned to a variable the variable is propagated trough the constraint network in forward and backward direction. If the variable violates any constraint the consistency management system will show this violation and its reason to the designer and give suggestions for resolving the conflict in the design consistency panel and typescript window. The constraint-based system obtains the expert knowledge through the knowledge acquisition system from various knowledge sources, which represent other requirements of the life cycle issues, formulated in terms of constraints, rules and procedures in the knowledge base. The system has a process optimisation module, which includes a rule-based algorithm and process feature table. This module provides selection of most feasible processes for the component subject to criteria such as tolerances, availability, surface finish, time and cost. The system provides designers with design of components at low cost, in shorter time and higher quality in the early design stages by avoiding design conflicts, maximum and economical use of the available manufacturing facilities, feasible process selection and optimisation and satisfaction of the requirements of the life cycle issues. Further details of the intelligent constraint-based system and cost estimation, process selection and optimisation is explained in chapter 4 and 5.

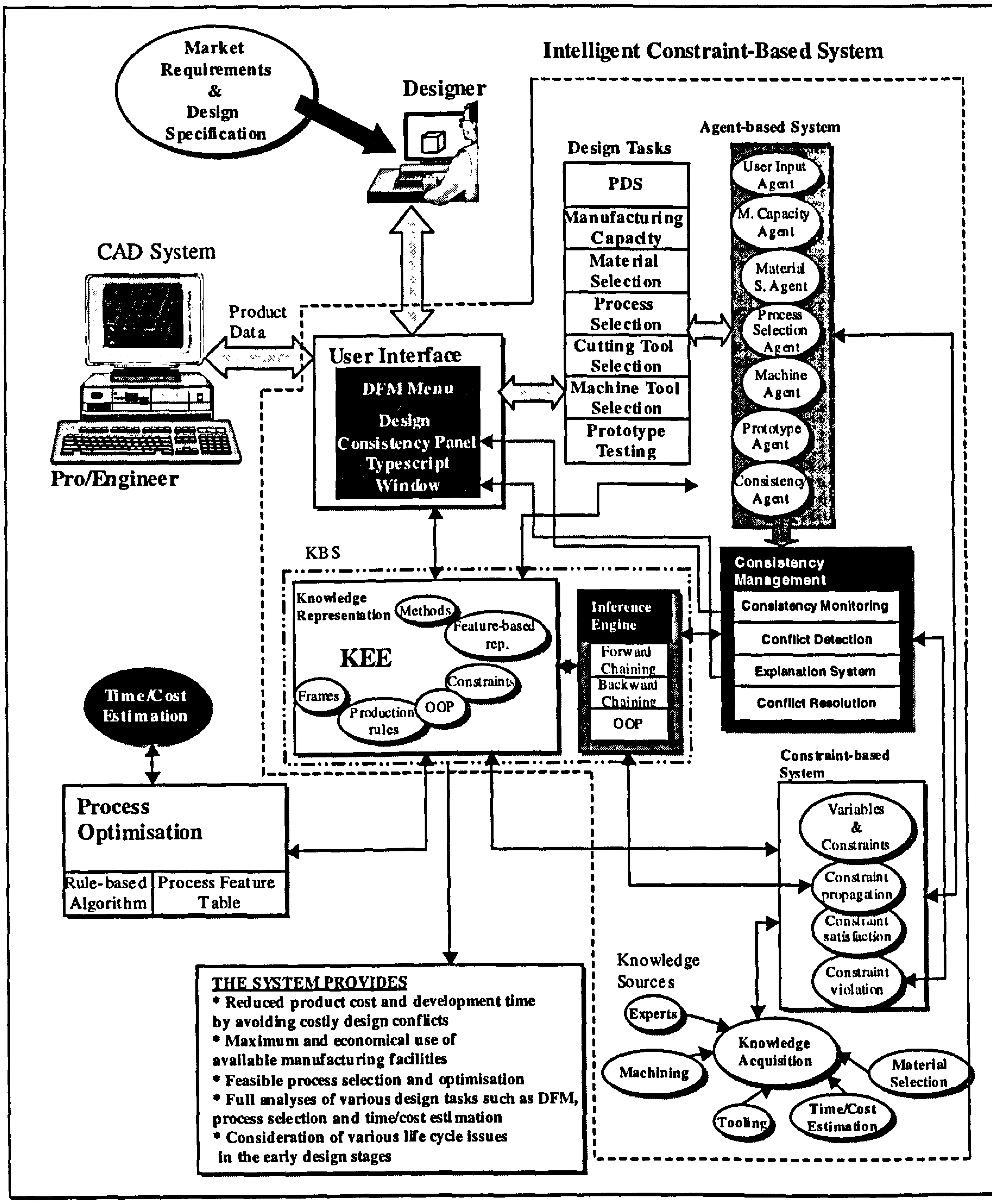


Figure 3-8 The Generic Integrated Platform for Supporting Concurrent Engineering

3.7 Summary

The proposed approach, which is presented in this chapter, provides a unique approach to concurrent product and process design. It is comprised of a CAD solid modelling system, user interface, design representation module, consistency manager module, constraint-based system, process optimisation and manufacturability analysis module and various knowledge sources.

The proposed approach presented in this chapter, has the following unique features:

- Concurrent consideration of downstream activities in the early design stages to achieve product designs, producible with the available manufacturing facilities, at low cost, reduced lead-time and high quality.
- It ensures that the design model is consistent with the design and manufacturing requirements, by providing the designers with recommendations on the design to avoid unexpected consequences leading to longer lead times and higher costs in the further design stages.
- Implementation of the constraint-based approach for modelling and handling design and manufacturing requirements is formulated as constraints for their effective use during the design process.
- Development of a consistency management module for the decision-making process during the design process to avoid conflicts arising from different design areas, leading to longer lead-times. It deals with the following tasks: constraint violation and satisfaction, conflict detection and resolution, consistency monitoring, and explanation system.
- Using the state-of-the-art knowledge representation techniques offered by KEE, such as OOP and production rules, to build the design model and its requirements, in a systematic and well-organised way to provide an effective interaction and communication between design and manufacturing areas.
- A user-friendly interface for providing the users with an interactive design environment to enable them to interact with the system easily via the utilisation of powerful features such as multiple-choice menus, images, method actuators, and design consistency panel.

- Process selection and manufacturability analysis module, which included a rule-based algorithm, provided the designer with the ability to analyse the design, select and optimise the available processes that are feasible subject to the predefined criteria.

CHAPTER 4

4 AN INTELLIGENT PROTOTYPE CONSTRAINT-BASED DESIGN SYSTEM

4.1 Overview

This chapter describes the details of the intelligent constraint-based design system for supporting concurrent product and process development, in order to achieve successful product designs. In this system, the design model and the product life cycle issues including PDS, DFM, Manufacturing Capacity, Process Selection, Time/Cost Estimation, Cutting and Machine Tool Selection, and Prototype Selection have been modelled as constraints, frames, production rules and objects. This ensures that analyses of the design are effectively carried out. The criteria and production rules necessary for analysing the design are also presented in this chapter. Various problem-solving techniques are implemented and integrated in order to run the system fast and efficiently and avoid long delays in the design process.

An information management system for design consistency was introduced to avoid conflicts, which may lead to unexpected and costly delays and design iterations in the design process. In order to achieve this, an overall design consistency approach was first presented. It was based on the constraint-based approach, which used a common database and an agent networking design representation technique. A conflict resolution strategy and a system for consistency monitoring were developed in order to deal with constraint violations. This was achieved by the development of the user-friendly interface. This is described in this chapter. It helped the designer to understand every aspect of the detailed analysis process as the design progresses.

4.2 Introduction

The product-life cycle process consists of several tasks such as product design specification (PDS), conceptual design, detail design, process selection, and optimisation. There are several requirements associated with these tasks.

These requirements have to be taken into account in the early stages of the design process. Current trends force manufacturers to produce low cost and high quality products to keep their competitiveness. This can be achieved by the best use of manufacturing resources such as machine tools, cutting tools, labour and processes to minimise the amount of time spent adding cost. In order to achieve this, manufacturing requirements (manufacturing resources, manufacturing capabilities) must be represented and modelled in a way that allows the design model to be analysed by considering all of these requirements. This needs an environment where decision making activities proceed concurrently.

Concurrent Engineering allows the design team to consider the factors affecting product cost, lead-time, manufacturability and selection and evaluation of manufacturing processes, in the early stages of the design process. These factors are directly related to product life cycle issues and have a major impact on the process cost. The requirements of the life cycle issues generally exist in the form of constraints related to part features, feature-process relations, machine tools, cutting tools, cost and time. The representation and modelling of those requirements are very important during the design process and prevent users from becoming engaged in time-consuming iterations process. Constraint-based systems are useful tools that are used to model and handle design requirements. However, they should include an information management system for effective information exchange and decision-making activities between design tasks, such as manufacturability analysis, process selection, process time and cost estimation. Constraint-based systems should also offer flexibility to enable designers to attach new databases to the system.

Some research work has been carried out in the area of information modelling and management (Al-Ashaab and Young, 1995, and Al-Ashaab and Young, Unpublished Paper).

To achieve an effective management of the life-cycle constraints a communication network system should be provided within the different design and manufacturing areas. This requires the critical consideration of various tasks such as overall co-ordination, control, consistency, and data integrity to prevent costly design iterations.

This can be achieved by the integration of different design areas through establishing Local Area Networks (LANs), within an organisation in a consistent manner. Such integration should include a strategy for conflict resolution, to avoid disagreements within the different activities or areas. Research work in this area was conducted by several authors including Noble, 1993; Balasubramanyam and Norrie, 1996; Lander et al., 1996; and O'Grady et al., 1991.

4.3 Feature Representation

A feature is a generic entity, which possesses geometrical and topological information, which may be used for design of parts and communication between design, manufacturing, and other engineering tasks such as assembly, process selection, cost/time estimation and maintenance. Representation of features should be explicit in a form that matches manufacturing knowledge. Analysis of form features is directly associated with certain manufacturing processes, that have important effects on generating detailed process plans.

In this analysis, manufacturing form features are the lynch pin of the generation and optimisation of manufacturing processes and provide communication between designer and process planners. This allows consideration of how their decisions affect the product and process design. The use of manufacturing form features helps designers to simplify process planning by allowing considerations of certain manufacturing processes necessary for producing the component. Therefore, a feature-based representation technique has been used to represent the component and features, in greater detail, so that designers, process and assembly planners or an expert system can use the same model to carry out various design tasks. Generating a cost-effective process plan necessitates full definition of manufacturing form features in terms of topological and geometrical attributes.

For example, a slot is a form feature defined by parameters such as width, depth, locations, tolerance, process and surface finish. Based on these parameters, the manufacturing processes, set-ups, fixture and cutting tools can be chosen.

Some of the most common form features and 3-D solid model of an engine head are shown in Figure 4-1 and 4-2. The proposed model contains production rules and knowledge about the form features and the manufacturing processes. These rules manipulate the behaviour of the feature and process data, which is represented in a structured way, and effective format made to reach a feasible solution. Manufacturing environment capabilities (i.e. production size, maximum length, diameter, tolerance, surface finish, and tools) are contained in the rules.

Object-oriented representation of through holes is shown as follows.

(hole

with

(name :through-hole)

(diameter :10 mm)

(depth: 30 mm)

(depth/diameter_ratio: 3)

(dimensional_tolerance: ±0.002)

(x_distance: 100 mm)

(y_distance: 34 mm)

(first_process: drilling)

(second_process: grinding) (....................................))

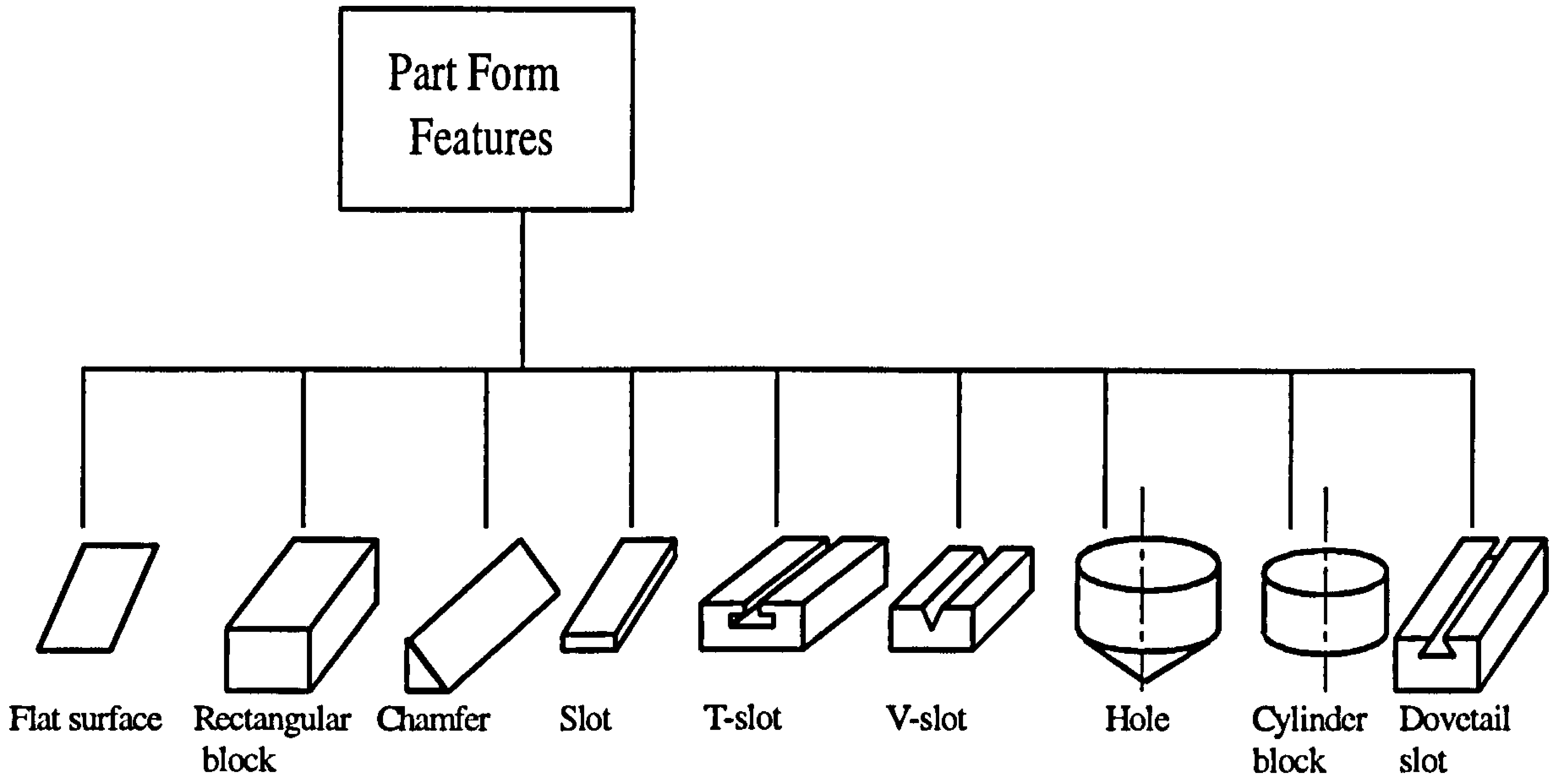


Figure 4-1 Manufacturing Form Features

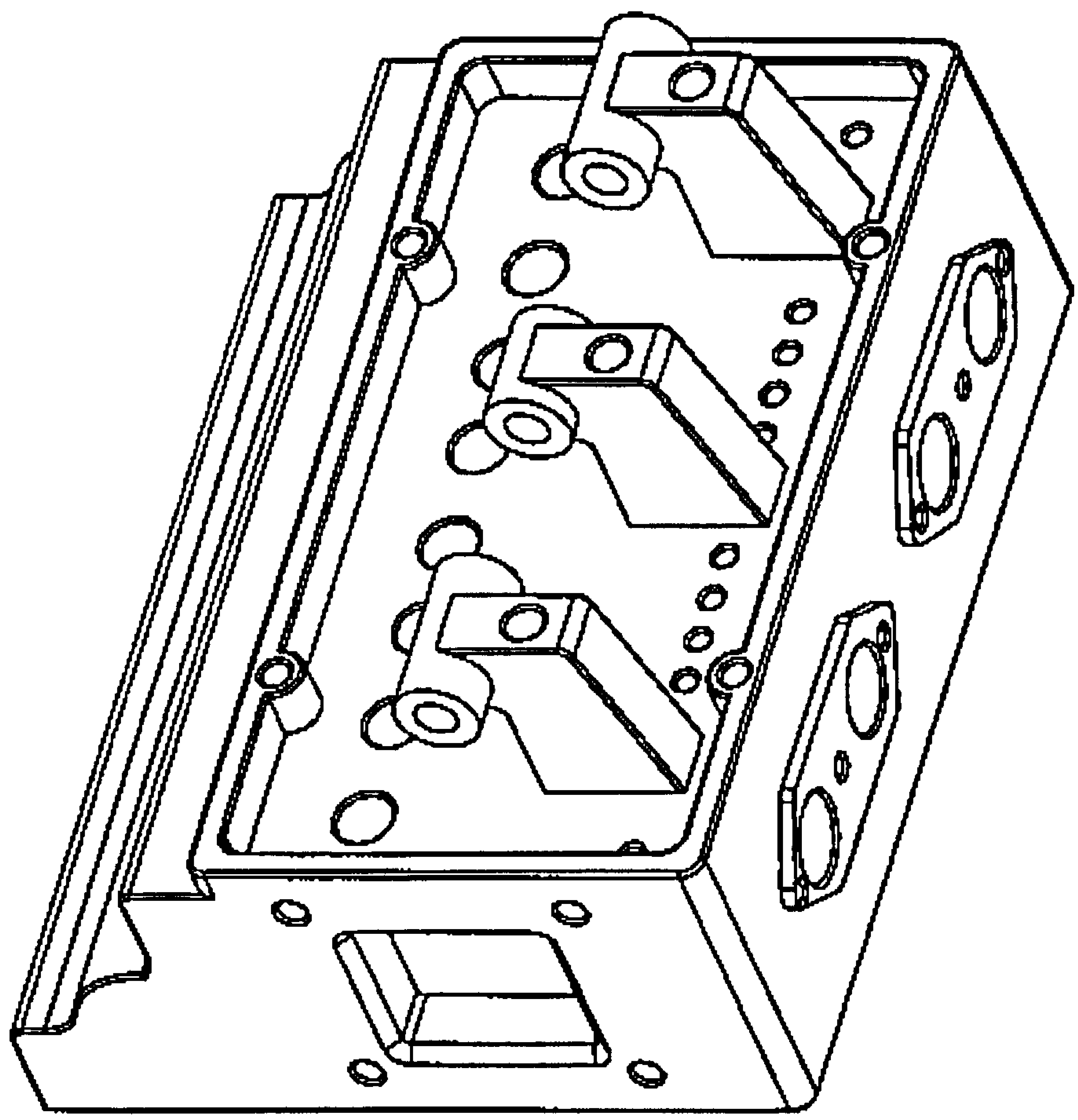


Figure 4-2 A 3-D Solid Model for An Engine Head

4.4 Representation of Design and Manufacturing Knowledge

In order to carry out necessary analysis, which will ensure the product's manufacturability, with the existing manufacturing facilities, the available processes, materials, machine tools, cutting tools and fixtures must be represented in the constraint forms. This will allow various analyses to be carried out in a consistent manner. The knowledge representation techniques, that have been used to represent the requirements of design and manufacturing, are described in detail in the following sections.

4.4.1 Constraints

Constraints are used to represent the information related to different aspects of the product life cycle, like the design requirements, which have to be met by the designed product. These requirements can be represented as constraints. For instance, from a process planner's point of view, the tolerance of a hole could be a constraint and the product cost another. Constraints represent certain limitations or restrictions on the design variables. Design and manufacture variables can be effectively held in a slot or a rule class and can be kept between certain values defined as constraints. In this research, design and manufacturing requirements are formulated as a set of constraints in slots of a unit, and in the production rules. Samples of the various types of constraints used in this research are illustrated below:

1. Domain (i.e. machine tools, cutting tools, manufacturing capacity, etc.)
2. Equations (i.e. $MRR = (\pi Dt^2 / 4) f N$ or $8 \geq d \leq 80\ mm$))
3. Production Rules (*If (feature is hole and surface roughness ≥ 6 and more rules) then (process is drilling)*)
4. Logical constraints (*Do you want to change the diameter?* (*YES* or *NO*))

In the example of production rules, shown below, the manufacturing variables of a form feature are defined as diameter, depth, lower_tolerance, upper_tolerance, and surface_finish. The lower_tolerance variable has its own constraint; >= ?lower)_tolerance 0.025 mm which means that the lower_tolerance must be equal to or greater than the limit 0.025mm).

An example of how the manufacturing requirements are formulated as constraints, in a rule class, is shown below. The flowchart of process selection for blind holes is shown in Figure 4-3.

```
(Blind_hole_rule_1
(if (?what is in blind.holes)
(the diameters of ?what is ?diameters)
(the depth of ?what is ?depth)
(the lower_tolerance of ?what is ?lower_tolerance)
(the upper_tolerance of ?what is ?upper_tolerance)
(the surface_finish of ?what is ?surface_finish)
(........)
(lisp (>= ?lower_tolerance 0.025)
(lisp (>= ?upper_tolerance 0.15)
(lisp (>= ?surface_finish 1.6)
(........)
then
(lisp (format t "****The possible process for ~d is
drilling, end_milling and edm..****" ?what))
(the volume of ?what is (lisp (* (* (/ π 4)
 (* ?diameters ?diameters)) ?depth)))
(the first.process.selection of ?what is ok)
(the possible.process_1 of ?what is drilling/counterboring)
(the possible.process_2 of ?what is milling)
(the possible.process_3 of ?what is edm)
(..........))))
```

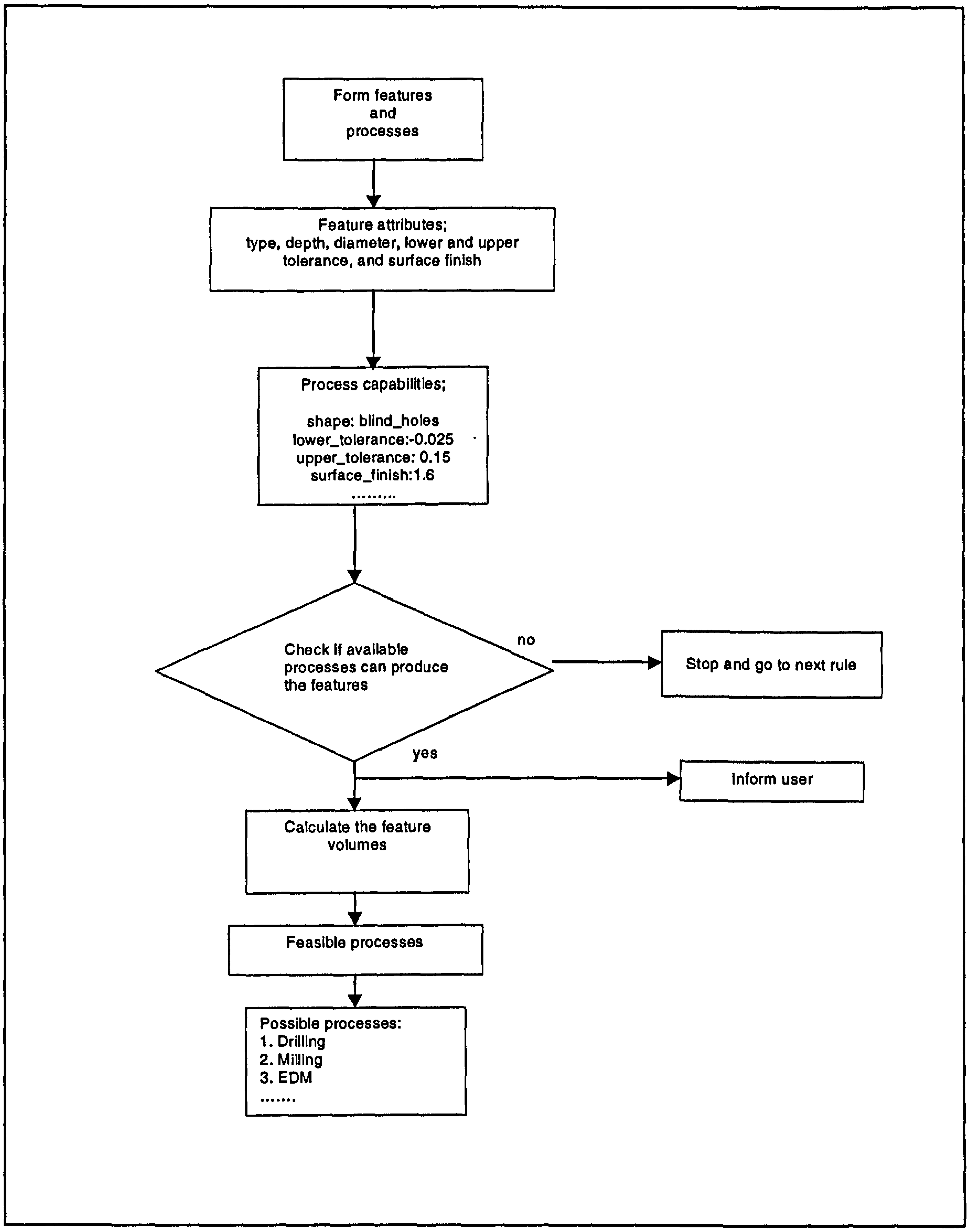


Figure 4-3 The Flowchart of Process Selection for Blind Holes

4.4.2 Frames

Frames, as knowledge representation techniques, are used for storing interconnected information about a design. Knowledge representation of stereotypical objects can be achieved effectively, using the frames, which consist of a name and a number of slots. The frames in the KEE are very flexible. Images and active values, to any slot, can be attached in order to monitor value changes. Facets, as attributes of slots (i.e. value class, inheritance role, max. and min. cardinality), enable the user to define values of slots and the way they are passed down the hierarchy. The example, shown in Figure 4-4, demonstrates how the product design specification can be represented in the form of frames.

Super class: *Product Specification*

Sub-classes: *Part, Manufacturing Cell Capacity, Available Machine Tools*

Properties: (part type

```
(value ((lambda (self)
(with-keeio (setq choice (prompt-use 'choice-multiple
:choices '(rotational non-rotational)
:prompt "Please select one: "
:few-choices-mode 'menu))))))
(inheritance method)
(valueclass (#[Unit: method keedatatypes])) (default nil)
(activeimage(#[Unit:windowpane-availability-of-machine.constraints.
manufacture007])
. unique.values) (cardinality.min (1)) (cardinality.max (1)))

(length.....)
```

```
||| (Output) The THROUGH.HOLES Unit in MANUFACTURE007 Knowledge Base
Unit: THROUGH.HOLES in knowledge base MANUFACTURE007
Created by dan on 9-10-96 13:43:41
Modified by dan on 6-10-98 16:25:05
 Superclasses: TYPE.OF.HOLES
 Member Of: CLASSES in GENERICUNITS

Member slot: ACCESSIBILITY from PART.CONSTRAINTS
 Inheritance: OVERRIDE.VALUES
 ValueClass:
          (ONE.OF YES NO)
 Cardinality.Max: 3
 Cardinality.Min: 1
 Values: UNKNOWN

Member slot: APPROACH_DIRECTION from PART.CONSTRAINTS
 Inheritance: OVERRIDE.VALUES
 ValueClass:
          (ONE.OF X Y Z -X -Y -Z)
 Cardinality.Max: 1
 Cardinality.Min: 1
 Values: UNKNOWN

Member slot: AXIS_DIRECTION from PART.CONSTRAINTS
 Inheritance: OVERRIDE.VALUES
 ValueClass:
          (ONE.OF X Y Z -X -Y -Z)
 Cardinality.Max: 1
 Cardinality.Min: 1
 Values: UNKNOWN

Member slot: A_KIND_OF from DESIGN.AND.MANUFACTURE.CONSTRAINTS
 Inheritance: OVERRIDE.VALUES
 ValueClass:
          (ONE.OF PART
             MATERIAL
             FEATURE
             CUTTING_TOOL
             MACHINE_TOOL
             PROCESS)
 Cardinality.Max: 1
 Cardinality.Min: 1
 Values: UNKNOWN

Member slot: CONTAINED_IN from PART.CONSTRAINTS
 Inheritance: OVERRIDE.VALUES
 Values: UNKNOWN

Member slot: CONTAINS_FEATURE from PART.CONSTRAINTS
 Inheritance: OVERRIDE.VALUES
 Values: UNKNOWN

Member slot: COST from DESIGN.AND.MANUFACTURE.CONSTRAINTS
 Inheritance: OVERRIDE.VALUES
 Values: UNKNOWN

Member slot: COST.CALCULATION from DESIGN.AND.MANUFACTURE.CONSTR
          AINTS
 Inheritance: OVERRIDE.VALUES
 ValueClass:
```

Figure 4-4 Frame-Based Representation

4.4.3 Production Rules

Knowledge and facts, about a problem domain, can be represented as rules in the form 'IF premises **THEN**' conclusion. The production rules store design and manufacturing constraints in the system. In the developed system, production rules have been used, as values of unit attributes (slots) and can be manipulated and inherited from higher classes to sub-classes.

The production rules, included in the slots, enable a complex-structured rules system to interact with different sets of rules associated with different units. A combination of these rules with methods, which are LISP functions stored as a value of a slot, makes the rule system run quickly and efficiently. As an example, in the prototype-testing-rule-1, shown below, the total manufacturing cost is calculated using LISP functions.

The Lisp command the UNITMSG sends a message to the PART unit, which passes the message to the TOTAL-COST method stored in a slot. The TOTAL-COST method performs the action for calculating the total process cost. The calculated value becomes the value for the TOTAL_MANUFACTURING_COST slot. The production rules are used to establish design and manufacturing constraints. An example of how the production rules can be used for prototype testing is also shown as follows.

(prototype-testing-rule-1

(if (the total_m_cost_control of part is ?total_ m_cost_control)

(?total_ m_cost_control = ok)

then

(the total_manufacturing_cost of part is (lisp (unitmsg 'part 'total-cost)))))

(protototpye-testing-rule-2

(if (the total_manufacturing_cost of part is ?total_manufacturing_cost of part)

(the target_manufacturing_cost of part is ?target_manufacturing_cost)

(lisp (>= ?total_manufacturing_cost of part ?target_manufacturing_cost))

then

(lisp (format t "~%The estimated manufacturing cost of part is higher than the proposed target manufacturing cost..The target manufacturing cost is ~D_1 \$ and the estimated manufacturing cost is ~D_2 \$..~%"

?target_manufacturing_cost

?total_manufacturing_cost)))

***(prototpye-testing-rule-3** (if (more rules))))*

4.4.4 Object-Oriented Programming

The object-oriented programming technique enables designers to model real world concepts as objects, which are collections of data grouped together in terms of similarities in their structure and behaviour (Sun Common Lisp 4.0 Object System, 1990). By using this technique, design and manufacturing objects, such as machine tools, cutting tools, features, material features, and machining elements are organised into various classes, represented as hierarchies (Figure 4-5).

The technique uses the concept of classes. Each class has a name and is divided into several sub-classes, which consist of a number of objects with a number of slots (attributes such as cutting speed, feed-rate, size, and tolerance). All classes can be divided into sub-divisions so that all components of the class are considered. An instance or a member of a class (i.e. machines, cutting tools, and materials) can be added to a sub-class to represent the available manufacturing resources of a company. Inheritance is an important characteristic of the object-oriented programming technique. It enables the designer to define a specific value in a higher class to be inherited to the lowest class of the hierarchy.

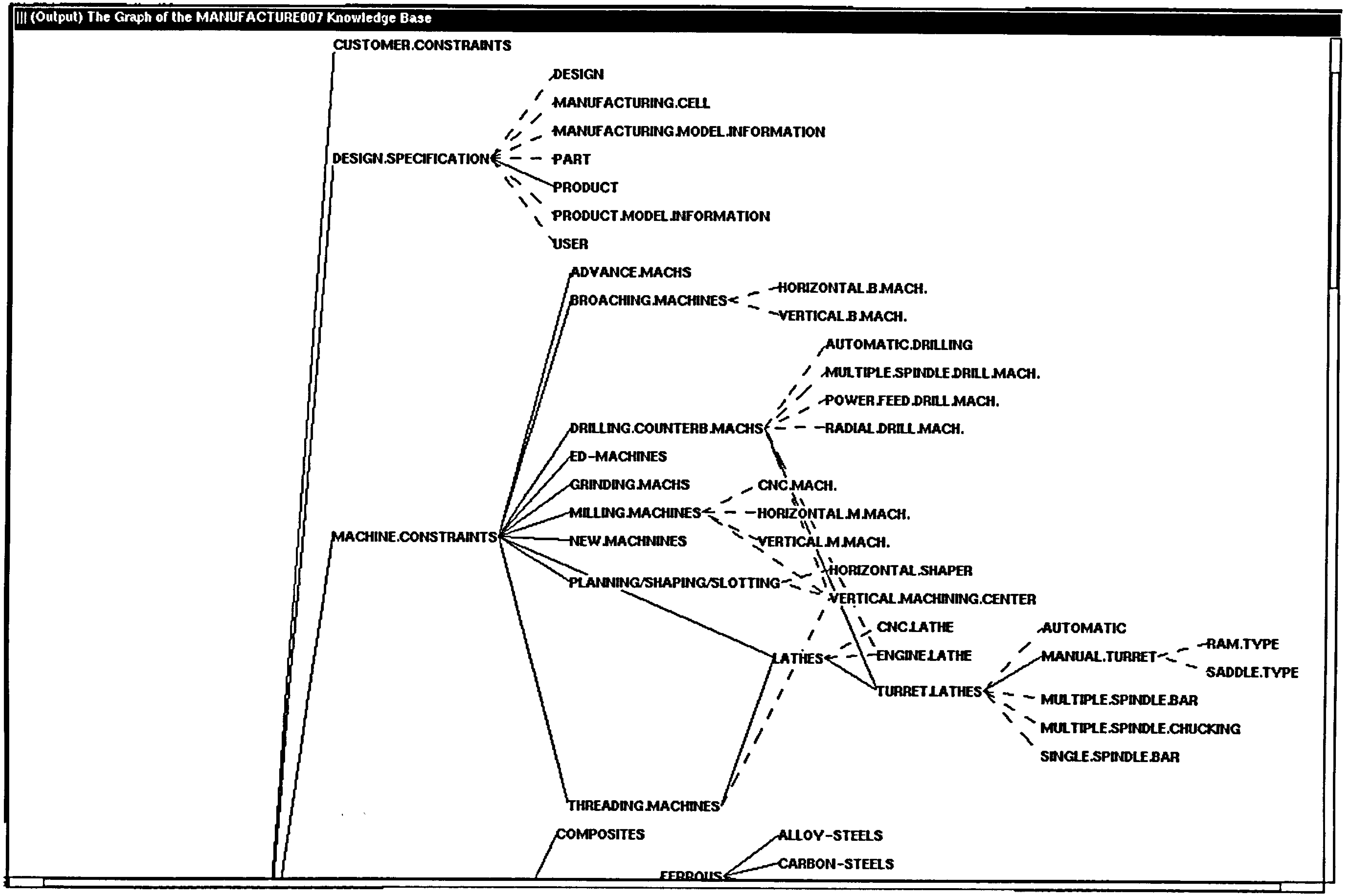


Figure 4-5 Object-Oriented Representation in the System

4.5 Design for Manufacturability

4.5.1 Manufacturing Capacity Checking

The aim of the manufacturing capacity checking is to produce the intended product consistent with the product design specification provided by the designer and to ensure that the product can be manufactured with the existing manufacturing facilities. This is shown in Figure 4-6. To achieve this, requirements associated with the available processes and capabilities, machine tools and dimensions, maximum production volume of the manufacturing cell should be clearly known. The developed system includes these requirements in the form of constraints, production rules and objects.

```
KEE Typescript Window
*******************************************
    WELCOME TO CE ENVIRONMENT
*******************************************

What is the NAME of USER ?

What is the DATE of DESIGN ?

What is the NAME of PART ?

What is the PRODUCTION_QUANTITY of PART ?


-----------------------------------------------------------------
>>>>>>THE UNITS FOR THE FOLLOWING QUESTIONS ARE $ AND MIN.,
 AND FOR PART DIMENSIONS THE UNIT IS MM<<<<<
-----------------------------------------------------------------

What is the TARGET_PROCESS_COST of PART ?

What is the TARGET_PROCESS_TIME of PART ?

What is the MAX.LENGTH of PART ?


-------------------------------------------------------------------
>>>> If you want to add a new machine to the following machine list
 please enter its name and specification..
Type *YES* or  *NO* for the availability of the machines<<<<

-------------------------------------------------------------------

What is in class MACHINE.CONSTRAINTS
other than AUTOMATIC.DRILLING, ENGINE.LATHE,
RADIAL.DRILL.MACH.,
POWER.FEED.DRILL.MACH.,
MULTIPLE.SPINDLE.DRILL.MACH.,
VERTICAL.MACHINING.CENTER,
SINGLE.SPINDLE.BAR,
MULTIPLE.SPINDLE.CHUCKING,
MULTIPLE.SPINDLE.BAR, AUTOMATIC,
SADDLE.TYPE, RAM.TYPE, CNC.LATHE,
HORIZONTAL.SHAPER, VERTICAL.M.MACH.,
HORIZONTAL.M.MACH., CNC.MACH.,
VERTICAL.B.MACH., HORIZONTAL.B.MACH.  : ?


---------------------------------------------------------------------
>>>> Please answer -YES- or -NO- to the next question for the machines
 available in your manufacturing cell..
The unit for the tool life replacement cost is $/min...<<<<

---------------------------------------------------------------------

For what unit's MACHINE.AVAILABILITY would you like to provide new values ?
```

Figure 4-6 Product Design Specification

4.5.1.1 Criteria for Manufacturing Capacity Checking

The criteria considered for the manufacturing capacity checking are as follows:

Production volume:

Maximum production volume per shift,

Minimum production volume per shift.

Length:

Maximum producible length that can be produced within the manufacturing cell,

Minimum producible length that can be produced within the manufacturing cell.

Width:

Maximum producible width that can be produced within the manufacturing cell,

Minimum producible width that can be produced within the manufacturing cell.

Height:

Maximum producible height that can be produced within the manufacturing cell,

Minimum producible height that can be produced within the manufacturing cell.

Diameter:

Maximum producible hole diameter that can be produced within the manufacturing cell,

Minimum producible hole diameter that can be produced within the manufacturing cell.

Other requirements:

Maximum horse power (HP) of Machine tools.

4.5.1.2 Manufacturing Capacity Rules

Manufacturing capacity checking rules were developed and based on the criteria set out in section 4.5.1.1. They were written in LISP (Tell and Ask language). Some of these rules and the flowchart, for checking the manufacturing capacity, are set out in Figure 4-7 and 4-8.

emacs: Emacs @ eng1

```
(part.dimension.change_1
  (if (the heigth.control
           of
           part
           is
           ?heigth.control)
      (?heigth.control = out.of.range)
      (the max.heigth of part is ?max.heigth)
      then
      (delete (the heigth.control of part is ?heigth.control))
      (delete (the max.heigth of part is ?max.heigth))
      (change.to
        (the max.heigth
             of
             part
             is
             (lisp (unitmsg 'part 'heigth.change))))))
 (part.dimension.change_2
   (if (the width.control of part is ?width.control)
       (?width.control = out.of.range)
       (the max.width of part is ?max.width)
       then
       (delete (the width.control of part is ?width.control))
       (delete (the max.width of part is ?max.width))
       (change.to
         (the max.width
              of
              part
              is
              (lisp (unitmsg 'part 'width.change))))))
 (part.dimension.change_3
   (if (the length.control
            of
            part
            is
            ?length.control)
       (?length.control = out.of.range)
       (the max.length of part is ?max.length)
       then
       (delete (the length.control of part is ?length.control))
       (delete (the max.length of part is ?length))
       (change.to
         (the max.length
              of
              part
              is
              (lisp (unitmsg 'part 'length.change))))))
 (part_height_rule_1
   (if (the max.heigth of part is ?max.heigth)
       (the maximum.manufacturable.heigth
            of
            manufacturing.cell
            is
            ?maximum.manufacturable.heigth)
       (the minimum.manufacturable.heigth
-----Emacs: kedit.lisp          (Lisp)----Top-------------------
```

emacs: Emacs @ eng1

```
            manufacturing.cell
            is
            ?minimum.manufacturable.heigth)
       (lisp (<= ?max.heigth ?maximum.manufacturable.heigth))
       (lisp (>= ?max.heigth ?minimum.manufacturable.heigth))
       then
       (lisp
         (format t
             "
~%
=============================================================================
THE HEIGTH OF PART IS ~D mm AND ITS IS SUITABLE FOR THE MANUFACTURING.CELL
WHOSE MAX.MANUFACTURABLE.HEIGTH IS BETWEEN ~D mm AND ~D mm...
=============================================================================~%"
                  ?max.heigth
                  ?minimum.manufacturable.heigth
                  ?maximum.manufacturable.heigth))
       (the heigth.control of part is within.the.range)))
 (part_height_rule_2
   (if (the max.heigth of part is ?max.heigth)
       (the maximum.manufacturable.heigth
            of
            manufacturing.cell
            is
            ?maximum.manufacturable.heigth)
       (the minimum.manufacturable.heigth
            of
            manufacturing.cell
            is
            ?minimum.manufacturable.heigth)
       (or (lisp (>= ?max.heigth ?maximum.manufacturable.heigth))
           (lisp (<= ?max.heigth ?minimum.manufacturable.heigth)))
       then
       (lisp
         (format t
             "
~%
===========================================================================================
THE HEIGTH OF PART IS ~D mm AND IT IS NOT WITHIN THE CAPABILITY OF THE MANUFACTURING CELL,
IT SHOULD BE BETWEEN ~D mm AND ~D mm...PLEASE CHANGE IT TO GO ON TO THE NEXT ANALYSIS AT
THE PROMPT....
===========================================================================================~%"
                  ?max.heigth
                  ?minimum.manufacturable.heigth
                  ?maximum.manufacturable.heigth))
       (the heigth.control of part is out.of.range)))
 (part_length_rule_1
   (if (the max.length of part is ?max.length)
       (the maximum.manufacturable.length
            of
            manufacturing.cell
            is
            ?maximum.manufacturable.length)
       (the minimum.manufacturable.length
            of
-----Emacs: kedit.lisp          (Lisp)----16%-------------------
```

Figure 4-7 Manufacturing Capacity Checking Rules

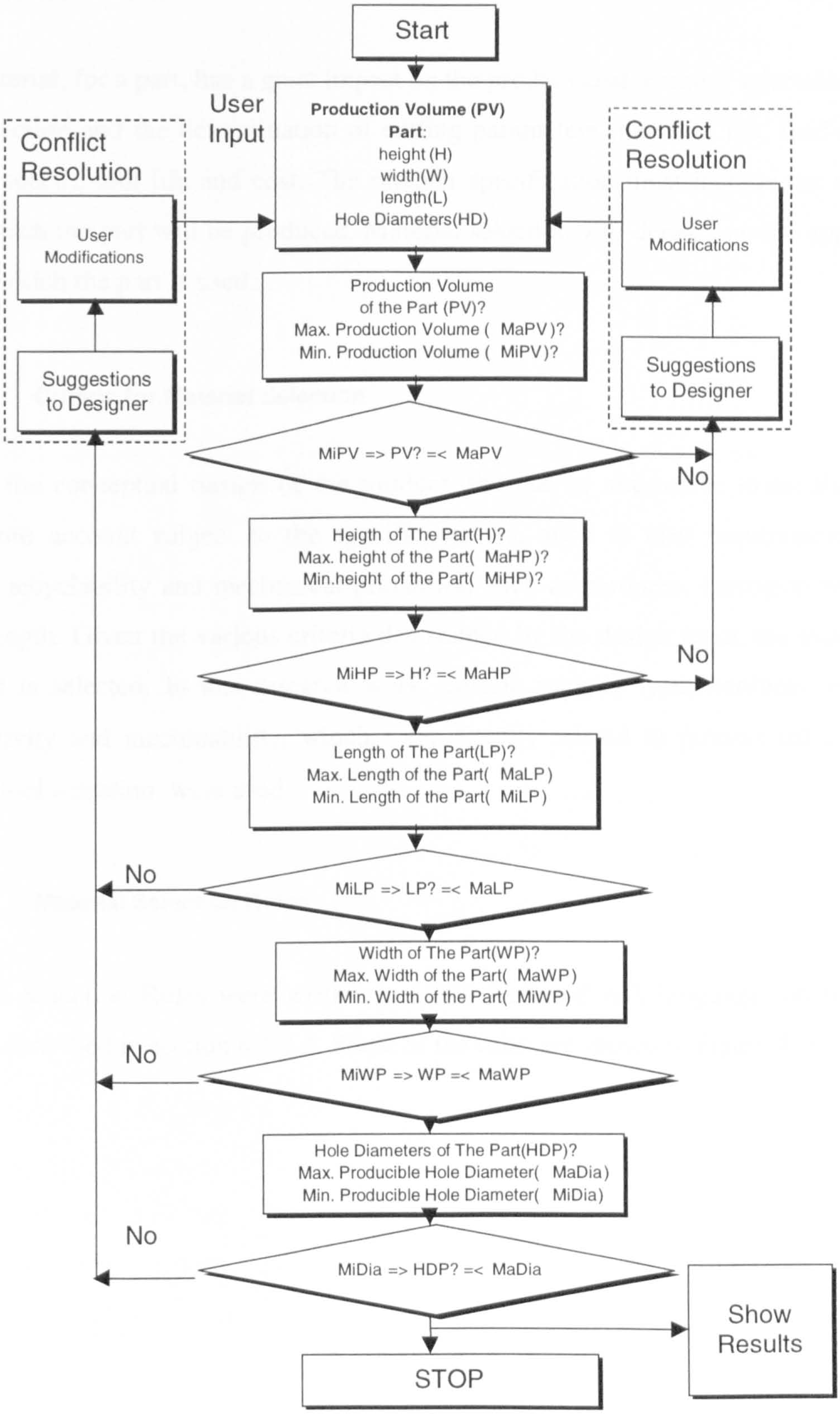


Figure 4-8 The Flowchart for Manufacturing Capacity Checking

4.5.2 Material Selection

The material, for a part, has a great impact on the product cost, process selection, cutting tool selection and the determination of cutting parameters (depth of cut, feed-rate and cutting speed), tool life and cost. The product specification must include the material, from which the part will be produced. Material selection will depend on the application area in which the part is used.

4.5.2.1 Criteria for Material Selection

During the conceptual design of the product, the use of alternative materials can be taken into account subject to the specific criteria, such as user requirements, cost, weight, recyclability and mechanical properties, such as hardness, corrosion resistance and strength. Given the various criteria determined by the design team, the material for the part is selected. In this research work, criteria such as type, hardness, electrical conductivity and machinability, which were directly related to process selection and cutting tool selection, were used.

4.5.2.2 Material Selection Rules

Material Selection Rules were written in LISP (Tell and Ask language) based on the criteria described in section 4.5.2.1. Some of the rules are shown in Figure 4-9.

```
KEE Typescript Window

==========================================================================================
>>>> PLEASE ENTER THE FOLLOWING INFORMATION ABOUT THE SELECTED MATERIAL PROPERTIES...
THE UNIT ARE $ FOR COST, MACHINABLITY VALUE BETWEEN 1-100, FOR TENSILE STRENGTH N/MM2,
THE UNIT FOR THE REST IS METRIC AND, FOR AREA AND DIMENSIONS ARE MM2 AND MM, AND FOR WEIGHT IT I
S KG....

 PLEASE CONSIDER THE FOLLOWING CRITERIA FOR MATERIAL SELECTION FOR THE CYLINDER HEAD.
 THE CHOICE OF MATERIAL FOR THE CYLINDER HEAD IS GENERALLY RESTRICTED TO GRAY CAST IRON
 AND ALUMINIUM ALLOYS..CAST IRON IS CHEAPER THAN ALUMINIUM ALLOYS..ALUMINUM HAS THE HALF
 THE WEIGHT OF EQUIVALENT CAST-IRON HEAD AND ITS THERMAL CONDUCTIVITY IS THREE TIME BETTER
 THAN CAST IRON..THE CORROSION RESISTANCE OF ALUMINIUM ALLOYS IS NOT SO GOOD AS CAST
 IRON'S. ALUMINIUM IS SOFTER THAN CAST IRON, THEREFORE MORE CARE NEEDED DURING MAINTENANCE..<<<<
==========================================================================================

What is in class ALLOY-STEELS ?

What is in class CAST-IRONS ?

What is in class STAINLESS-STEEL ?

For what unit's CLASS-HARDNESS would you like to provide new values ?
```

Figure 4-9 Material Selection (Heisler, 1985)

4.5.3 Manufacturing Process Selection, Optimisation and Time/Cost Estimation

Manufacturing process selection, optimisation and time/cost estimation are the important elements in design for manufacture. Process selection requires the consideration of topological and geometrical attributes of the form features, which are to be manufactured. These attributes have to be cognisant with the constraints in the available processes of a manufacturing cell. The optimisation of the processes depends on a set of criteria such as process time/cost and the selected processes for making the component. This is discussed further in chapter 5.

4.5.4 Cutting Tool Selection

The selection of the cutting tools for the part is generally carried out after the manufacturing processes have been selected. The cutting tool selection requires information from different domains (material selection, process selection, the design model, and the geometrical and topological attributes of its features). Also, it needs the available cutting tools and their constraints to be included in the knowledge base to ensure the utilisation of the cutting tools available in the manufacturing cell. The developed system enables the designers to add new cutting tools to the knowledge base.

4.5.4.1 Criteria for Cutting Tool Selection

In order to select cutting tools the specification of the selected material, the part and features information and available cutting tools should be known. A number of criteria for the cutting tool selection were considered as follows:

Workpiece:

- Type of material,
- Material hardness.

Feature:

- Feature type,
- Diameter for holes,
- Length,
- Round of corners for slots,
- Width,
- Height of feature.

Cutting tools:

- Cost of cutting tools,
- Diameter of cutting tools,
- Type of cutting tools,
- Tool material.

4.5.4.2 Cutting Tool Selection Rules

Production rules for the cutting tool selection were written in LISP (Tell and Ask language) based on the criteria described in section 4.5.4.1. Some of the rules and flowchart of cutting tool selection for holes are shown in Figure 4-10 and 4-11.

```
emacs: Emacs @ eng1
((d_rule_1
   (if (?through.holes is in through.holes)
       (the diameters of ?through.holes is ?diameters)
       (?material.constraints is in material.constraints)
       (the hardness of ?material.constraints is ?hardness)
       (lisp (<= ?hardness 225))
       (?three-flute-core-drill is
                                in
                                three-flute-core-drill)
       (the diameter of ?three-flute-core-drill is ?diameter)
       (the cost_1 of ?three-flute-core-drill is ?cost_1)
       (lisp (>= ?diameters ?diameter))
       then
       (the selected.cutting.tools
            of
            ?through.holes
            is
            ?three-flute-core-drill)
       (lisp
         (format t
                 "
~%
===============================================================================================
                    THE RESULTS OF CUTTING TOOL SELECTION
===============================================================================================
FEATURE
===============================================================================================
~D  d: ~D mm
===============================================================================================
DRILLING TOOL                                                                d        TYPE    COST
===============================================================================================
~D                              ~D mm     HSS       ~D $
===============================================================================================~%"
                 ?through.holes
                 ?diameters
                 ?three-flute-core-drill
                 ?diameter
                 ?cost_1))))
  (d_rule_2 nil)
  (m_rule_1
    (if (?block-slot is in block-slot)
        (the width of ?block-slot is ?width)
        (the length of ?block-slot is ?length)
        (the radius of ?block-slot is ?radius)
        (?material.constraints is in material.constraints)
        (the hardness of ?material.constraints is ?hardness)
        (lisp (<= ?hardness 225))
        (?end.milling.cutter is in end.milling.cutter)
        (the diameter of ?end.milling.cutter is ?diameter)
        (the cost_1 of ?end.milling.cutter is ?cost_1)
-----Emacs: kedit.lisp           (Lisp)----Top------------------------------------------
```

Figure 4-10 Rules for Cutting Tool Selection

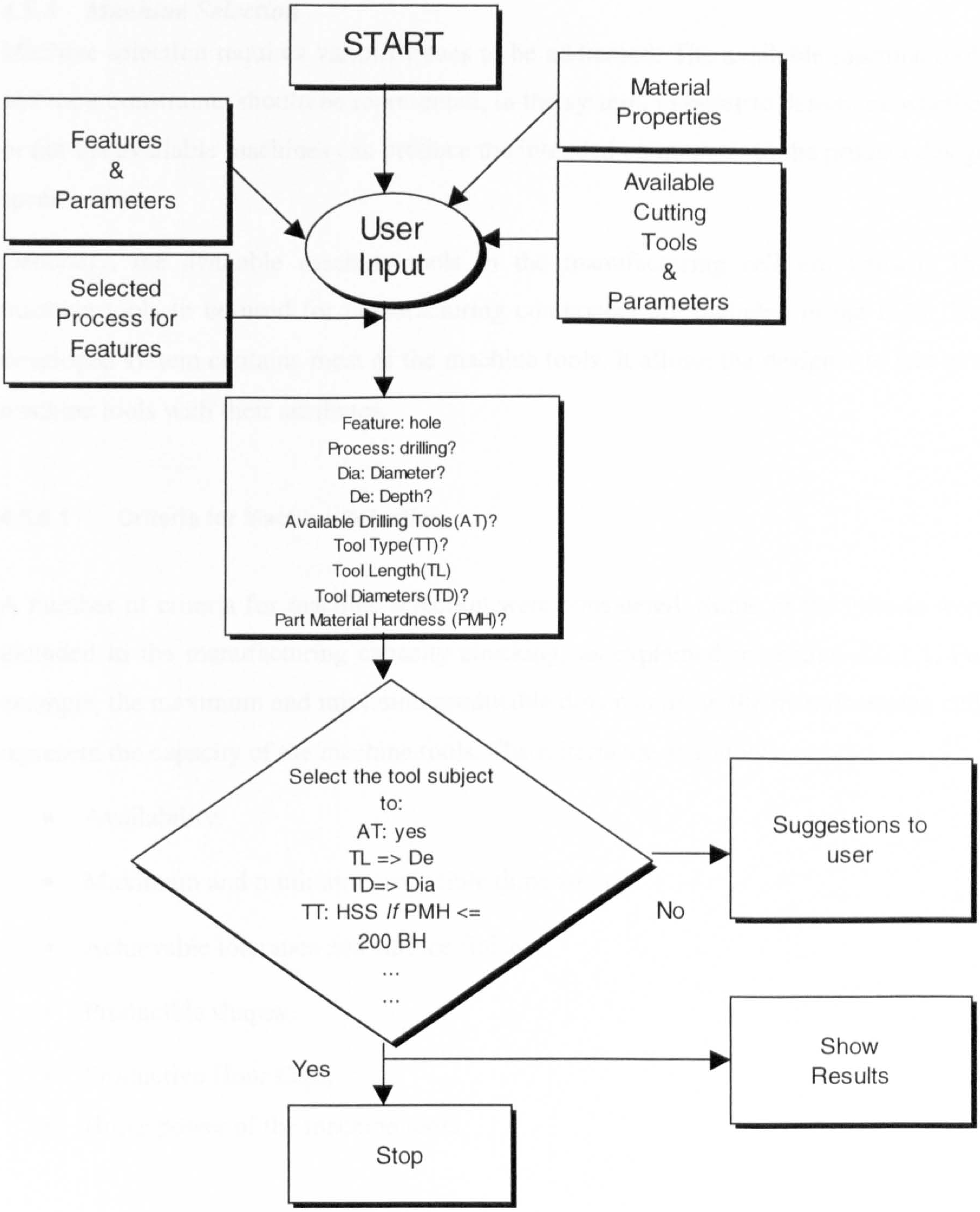


Figure 4-11 The Flowchart of Cutting Tool Selection for Holes

4.5.5 Machine Selection

Machine selection requires various issues to be addressed. The available machine tools and their constraints should be represented, in the system, in order to determine whether or not the available machines can produce the intended component to the product design specification.

Generally, the available machine tools in the manufacturing cell are known. The machine tools to be used for manufacturing component are included in the PDS. The developed system contains most of the machine tools. It allows the designer to add new machine tools with their attributes.

4.5.5.1 Criteria for Machine Selection

A number of criteria for machine selection were considered. Some of the criteria were included in the manufacturing capacity checking, as explained in section 4.5.1.1. For example, the maximum and minimum producible dimensions, in the manufacturing cell, represent the capacity of the machine tools. The criteria are as follows:

- Availability,
- Maximum and minimum producible dimensions,
- Achievable tolerance and surface finishes,
- Producible shapes,
- Productive Hour Cost,
- Horse power of the machine tools.

4.5.6 Prototype Testing of the Intended Part

When all analyses of the intended component are completed, prototype testing is carried out, subject to the criteria given by the user. Prototype testing allows the designer to ensure that the total process time and cost of the part are consistent with the targeted one defined in the PDS. At the end of the prototype testing, the designer will have the complete results and have an idea of the feasibility and ability to manufacture the intended part.

4.5.6.1 Criteria for Prototype Testing

Since prototype testing is subject to the estimated process time/cost of the part and the user requirements, the criteria for prototype testing were considered as follows:

The target process cost,

The target process time,

Estimated process cost,

Estimated process time.

4.5.6.2 Rules for Prototype Testing

The production rules for the prototype testing were written in LISP (Tell and Ask language), based on the criteria described, are set out in section 4.5.6.1. Some of the rules and flowchart of the prototype testing are shown in Figure 4-12 and 4-13.

```
emacs: Emacs @ eng1
((rule_1
   (if (the total_m_cost_control
            of
            part
            is
            ?total_m_cost_control)
       (?total_m_cost_control = ok)
       then
       (the total.manufacturing.cost
            of
            part
            is
            (lisp (unitmsg 'part 'total-cost)))))
  (rule_2
    (if (the total.manufacturing.cost
             of
             part
             is
             ?total.manufacturing.cost)
        (the target_process_cost
             of
             part
             is
             ?target_process_cost)
        (lisp (> ?total.manufacturing.cost ?target_process_cost))
        then
        (lisp
          (format t
                  "
~%
============================================================================
                           PROTOTYPE TESTING
============================================================================
THE ESTIMATED MANUFACTURING COST OF PART IS HIGHER THAN THE PROPOSED TARGET
MANUFACTURING COST..THE TARGET MANUFACTURING COST IS ~  $ AND THE ESTIMATED
MANUFACTURING COST IS ~  $..
============================================================================~%"
                  ?target_process_cost
                  ?total.manufacturing.cost))))
  (rule_3
    (if (the total.manufacturing.cost of part is ?total.manufacturing.cost)
        (the target_process_cost of part is ?target_process_cost)
        (lisp (<= ?total.manufacturing.cost ?target_process_cost))
        then
        (lisp
          (format t
                  "
~%
============================================================================
                                                 PROTOTYPE TESTING
============================================================================
THE ESTIMATED MANUFACTURING COST OF PART IS LOWER THAN THE PROPOSED TARGET
MANUFACTURING COST..THE TARGET MANUFACTURING COST IS ~  $ AND THE ESTIMATED
MANUFACTURING COST ~  $..
============================================================================~%"
-----Emacs: kedit.lisp          (Lisp)----Top------------------------------------
```

Figure 4-12 Prototype Testing Rules

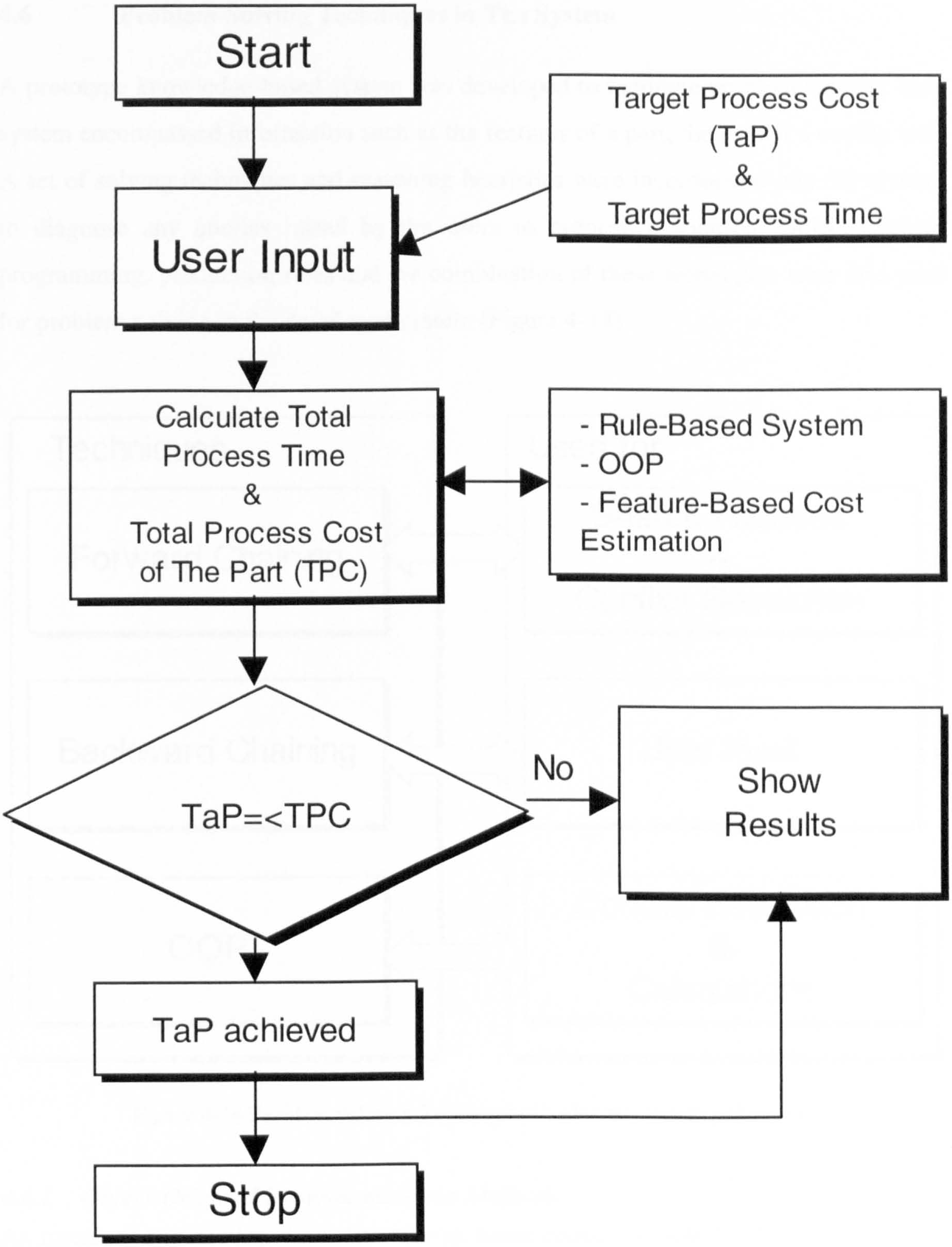


Figure 4-13 The Flowchart for Prototype Testing

4.6 Problem-Solving Techniques in The System

A prototype knowledge-based system was developed to facilitate problem solving. This system encompassed information such as the features of a part, the cost of a cutting tool. A set of solving techniques and reasoning heuristics were incorporated into the system, to diagnose any queries raised by the users to propose a solution. Object-oriented programming, production rules and the combination of these techniques were also used for problem solving in the developed system (Figure 4-14).

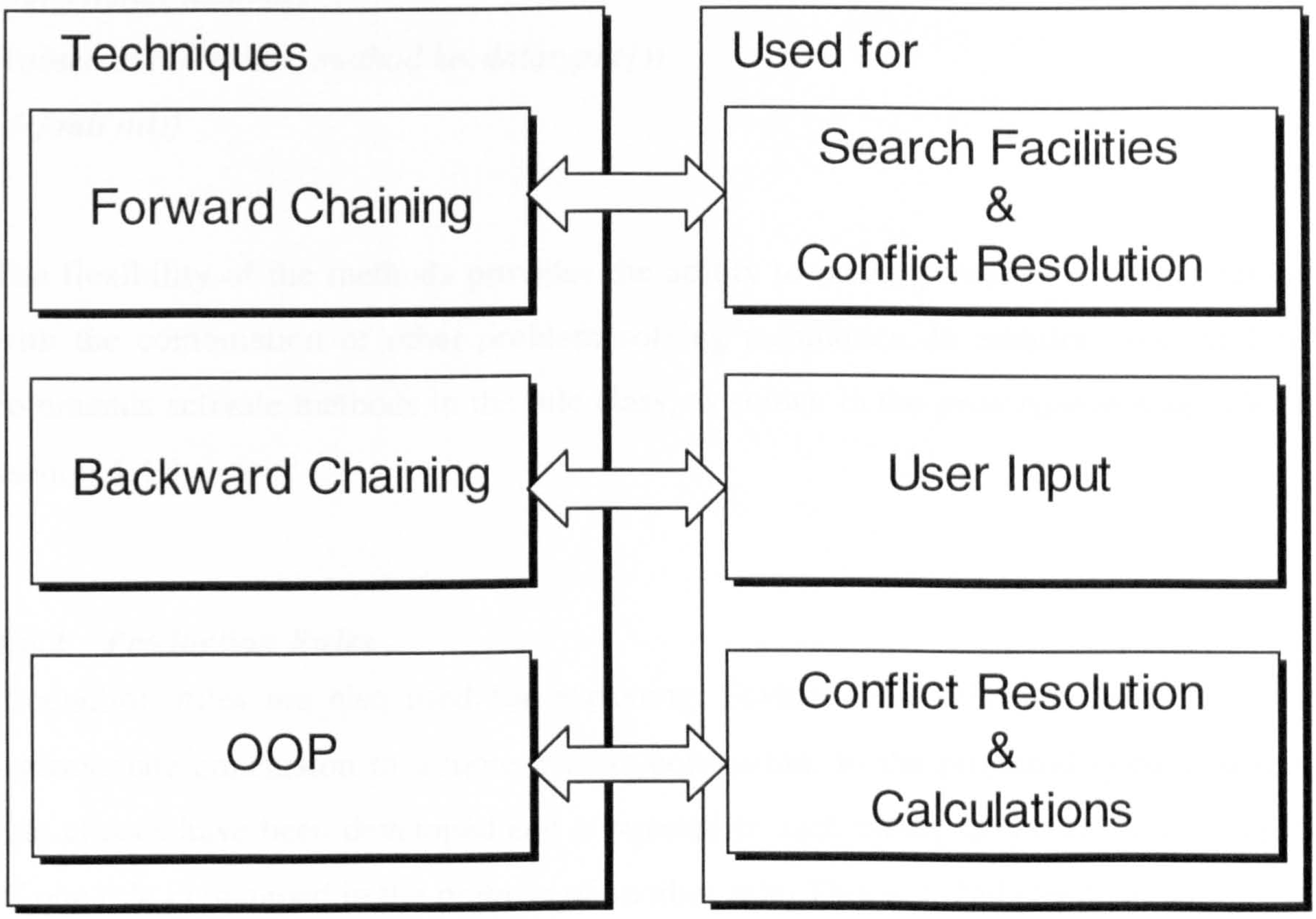


Figure 4-14 Problem Solution Techniques Used in the Developed System

4.6.1 Object-Oriented Programming via Methods

As mentioned in section 4.4.4, knowledge bases consist of objects. These objects can carry problem-solving behaviours in the form of a LISP function stored in the *TOTAL_COST* slot of the *PART* object as shown in section 4.4.3. The behaviour or a function of the method (which includes the LISP function) is stored inside the objects of the knowledge-based system.

The LISP functions, in the method slots, accomplish the given tasks such as the time/cost calculations of a part, This is illustrated in the example below.

(total_cost
(value
((lambda (thisunit)
(let ((cost_values (get.values 'part 'total_m_cost)))
(apply # ' + cost_values)))))
(inheritance method)
(valueclass (# [Unit: method keedatatypes]))
(default nil))

The flexibility of the methods provides the ability to create powerful rule applications with the combination of other problem solving techniques. In addition, special LISP commands activate methods in the rule class, as shown in the *prototype-testing-rules* in section 4.4.3.

4.6.2 Production Rules

Production rules are also used for reasoning. Several rules take the expert from an intermediate conclusion to a more precise conclusion. In the proposed system, several rule classes have been developed and connected to each other, such that the conclusion of one rule is included in the premise of another rule. This is called chaining. When rule chaining starts, conclusions of one rule class match the premises of another rule class. Chaining is used either in a forward or backward direction.

4.6.2.1 Forward chaining

Forward chaining tries to find implications of new information. It generally starts with new data input, by the user, or a different domain of a knowledge base. Therefore, it is called event-driven or data driven reasoning.

The system scans the rules, whose premises include the new fact. If the premises of a rule class are true, the conclusions of the rule class will be asserted in turn and become new information. The system then searches for the rule that possesses this new information, as a premise, and checks if all premises of this rule are true. This process continues until no rules are found with the matching premises.

4.6.2.2 Backward chaining

Backward chaining tries to verify a given fact or hypothesis. As the backward chaining starts with the goal of proving something, it is called goal-driven. The system scans the rules whose conclusions match a given fact to be proven. The fact is found verified if all the premises of the rule class in question can be verified in turn.

4.6.3 Combination of the Problem-Solving Techniques

In this research work, the OOP and production rules (with forward and backward chaining) were integrated and used in the system effectively. Using one technique is not sufficient to carry out the design tasks in a reasonable time, and rules classes may become very long and complex. Thus, maintenance, editing and updating is not an easy task for the designer. A reasoning technique may be good for certain applications. Each technique has its own advantages. For instance, the methods are very effective and fast for calculations, and can be activated in rule classes. Backward chaining is very effective to obtain input from the user via user-dialogues.

4.7 The Design Consistency Approach

Different design tasks, which include material selection, manufacturability analysis, process selection and optimisation, require that a huge amount of information be accessed and shared in the knowledge base, so that the various tasks can be carried out. This requires that the information transferred from one area to another is consistent (Gadient et al. 1997).

This also necessitates the addition of new information to the knowledge base, in order to accomplish specific tasks. As shown in Figure 4-15, several agents represent various design analyses. Each agent has a task to carry out and requires a common knowledge base to access the necessary information.

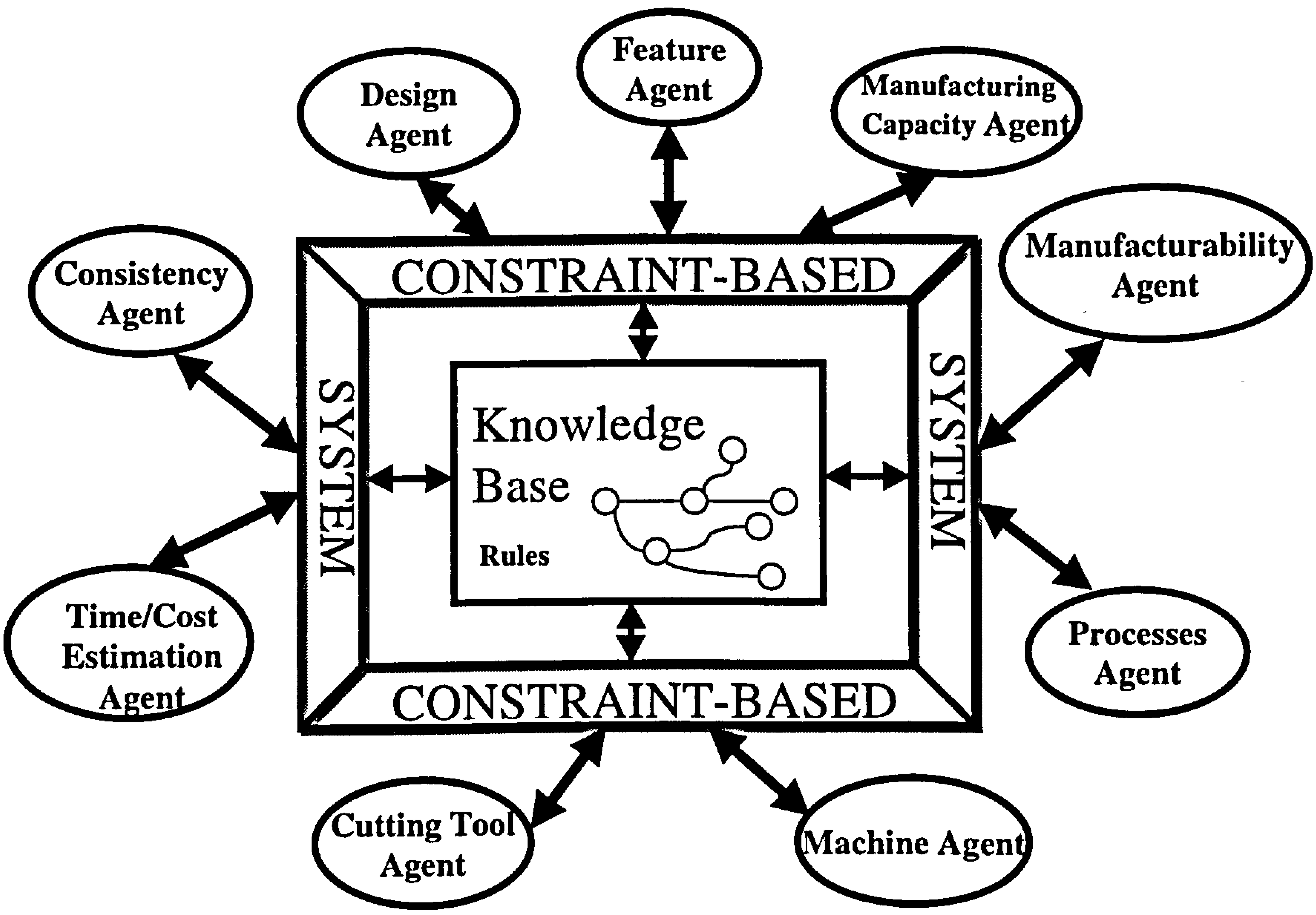


Figure 4-15 Overall Design Consistency in the System

An agent is an entity capable of solving locally generated problems through communication with other agents (Choi and Park, 1997). Agents have responsibilities for solving a given task in a design problem, such as process selection and/or capacity checking. Agents include a limited amount of program for dealing with a given sub-task, so that the task can be executed faster and at less cost. Each agent should interact with one another and exchange information between other agents, in order to accomplish the individual task.

4.7.1 Consistent Information Flow in the System

In order to ensure consistency in the constraint network, any new information from users or agents is propagated by the constraint-based system, which checks whether or not the new information causes constraint violation. Agents share information, while consistent information flow is achieved in the system. This is shown in Figure 4-16.

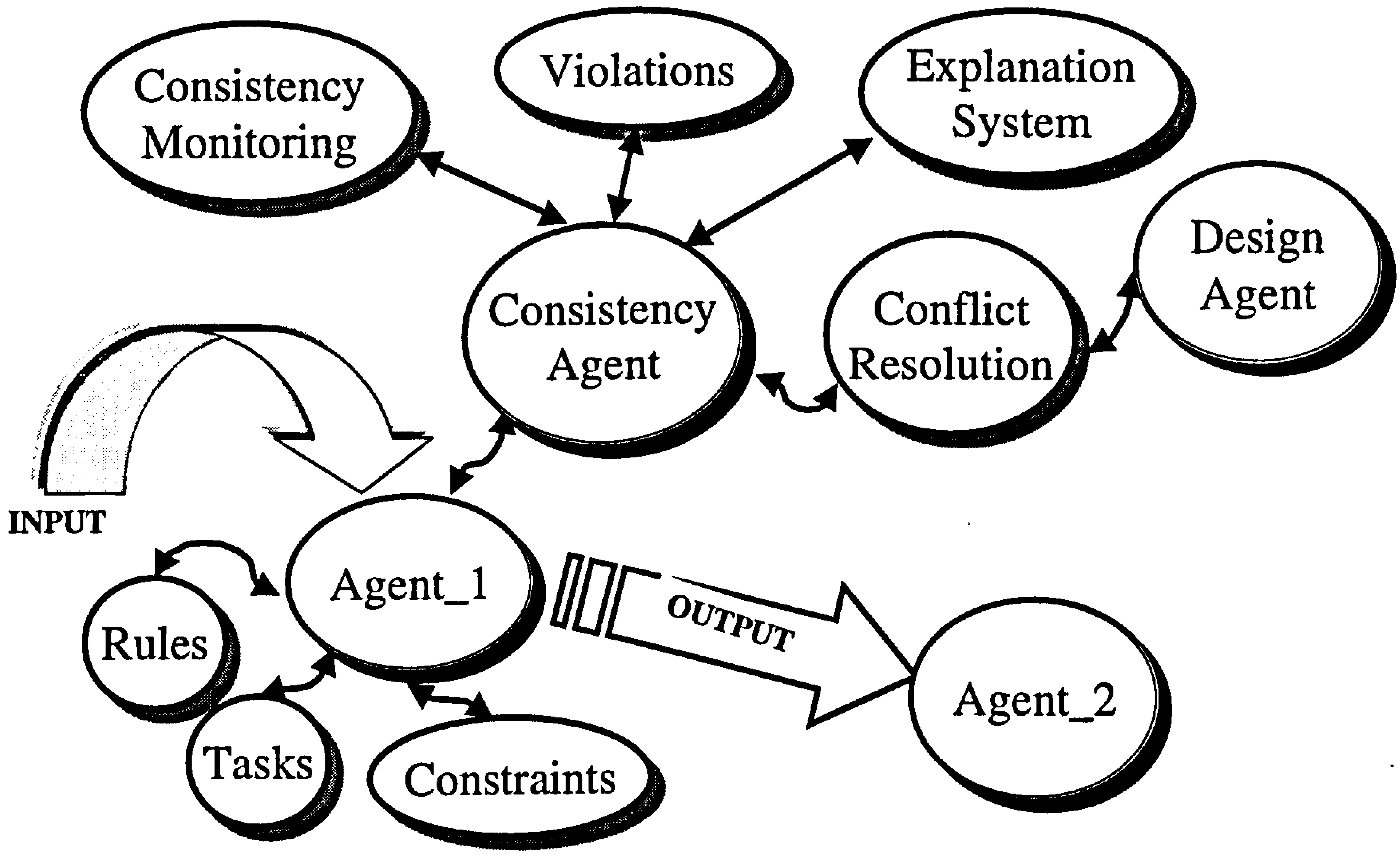
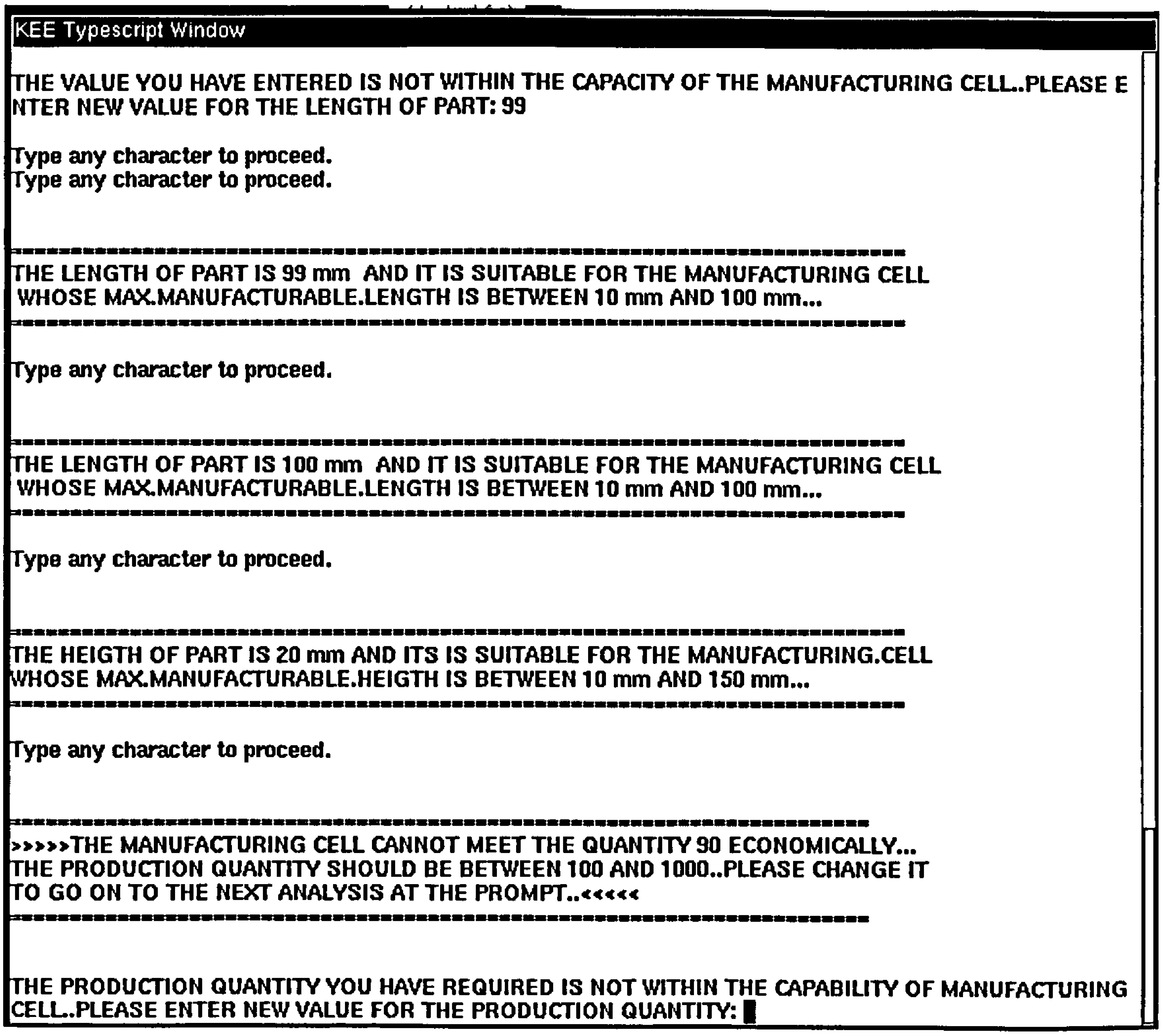


Figure 4-16 Information Flow between Different Aspects of Product's Life Cycle

An agent has to access design input from the knowledge base in order to complete its task. If the design input violates any constraints of the agent, it will be detected by the consistency agent. A message will be then sent to a method (of a slot) carrying a small program that is a function of LISP and is responsible for conflict resolution. Alternative solutions will be provided to users, by a menu, from which a design agent has to make selections. The system may ask the user to write the necessary information at the user-prompt.

4.7.2 *Conflict Resolution*

New information that does not violate the agent's constraints, is included in the knowledge base, so it can be utilised by other agents whenever required. The user interface immediately informs the user of conflicts. For instance, in the system, the manufacturing capacity agent contains constraints related to the production capacity. If the production quantity, defined by the user, is not between the constraints, the user will be informed by the user interface. A number of alternative solutions for sorting this problem will be displayed. The user will have to select from the suggested alternatives or type an answer at the prompt window, as shown in Figure 4-17. The production quantity required by the user will be consistent information, in the system, if it does not violate the constraints of the manufacturing capacity agent. Using this system, consistent information flow between different tasks of product's life cycle is achieved without costly design iterations usually occurred due to design conflicts.


KEE Typescript Window

THE VALUE YOU HAVE ENTERED IS NOT WITHIN THE CAPACITY OF THE MANUFACTURING CELL..PLEASE ENTER NEW VALUE FOR THE LENGTH OF PART: 99

Type any character to proceed.
Type any character to proceed.

THE LENGTH OF PART IS 99 mm AND IT IS SUITABLE FOR THE MANUFACTURING CELL
WHOSE MAX.MANUFACTURABLE.LENGTH IS BETWEEN 10 mm AND 100 mm...

Type any character to proceed.

THE LENGTH OF PART IS 100 mm AND IT IS SUITABLE FOR THE MANUFACTURING CELL
WHOSE MAX.MANUFACTURABLE.LENGTH IS BETWEEN 10 mm AND 100 mm...

Type any character to proceed.

THE HEIGTH OF PART IS 20 mm AND ITS IS SUITABLE FOR THE MANUFACTURING.CELL
WHOSE MAX.MANUFACTURABLE.HEIGTH IS BETWEEN 10 mm AND 150 mm...

Type any character to proceed.

»»»THE MANUFACTURING CELL CANNOT MEET THE QUANTITY 90 ECONOMICALLY...
THE PRODUCTION QUANTITY SHOULD BE BETWEEN 100 AND 1000..PLEASE CHANGE IT
TO GO ON TO THE NEXT ANALYSIS AT THE PROMPT..«««

THE PRODUCTION QUANTITY YOU HAVE REQUIRED IS NOT WITHIN THE CAPABILITY OF MANUFACTURING CELL..PLEASE ENTER NEW VALUE FOR THE PRODUCTION QUANTITY:

Figure 4-17 Conflict Resolution

4.7.3 Consistency Monitoring in the System

As part of the design consistency approach, the system enables the designer to monitor inconsistencies. This provides designers with visual displays of violation of the constraint. In the developed system, design variables are restricted by sets of constraints, which are represented in terms of rules, frames, and intervals. KEE (Knowledge Engineering Environment) offers various types of images and pictures that change their attributes (colours, shapes and texts) subject to the values to be monitored and checked by the designers. However, this does not give enough information about the inconsistencies.

An explanation system is also necessary to inform the designers of reasons for the detected inconsistencies. This is shown on the design consistency control panel. The "Typescript Window" is used for this purpose. When the system detects inconsistencies, it is shown on the panel. Then the reasons for the conflict are given in text form in the Typescript Window.

4.8 The User Interface

In order to provide good interaction between the system and the designer or the system user, a user-friendly design environment was developed. The development of the user interface was an important element of this research work. KEE, as an expert tool kit, provides good facilities for developing an interactive user interface. Since the user interface provides users with access to the system, it should meet the user requirements. This was described by Berrais, 1996.

The developed user interface is shown in Figure 4-18. It comprised of three major elements. The first element is the Concurrent Engineering Menu, which includes a DFM button which activates a multiple-choice menu for carrying out design tasks such as process selection, cutting tool selection and cost/time estimations. It also includes buttons for loading necessary files, starting the system and resetting the databases. In addition, the user interface contains a help menu. By using a mouse, the menus and buttons can be easily activated.

The second part of the user interface is the Design Consistency Control panel on which various active images are placed and linked to the design variables. The active images change their attributes, such as text and colour, to show the design inconsistencies. Any changes made to the variables are reflected in the images linked to them.

As the third element of the user interface, the Typescript Window provides the designers with the text displays on the reasons for conflicts, results of the analyses carried out, suggestions for the resolution of the conflict and a prompt where at the designer must type answers and queries.

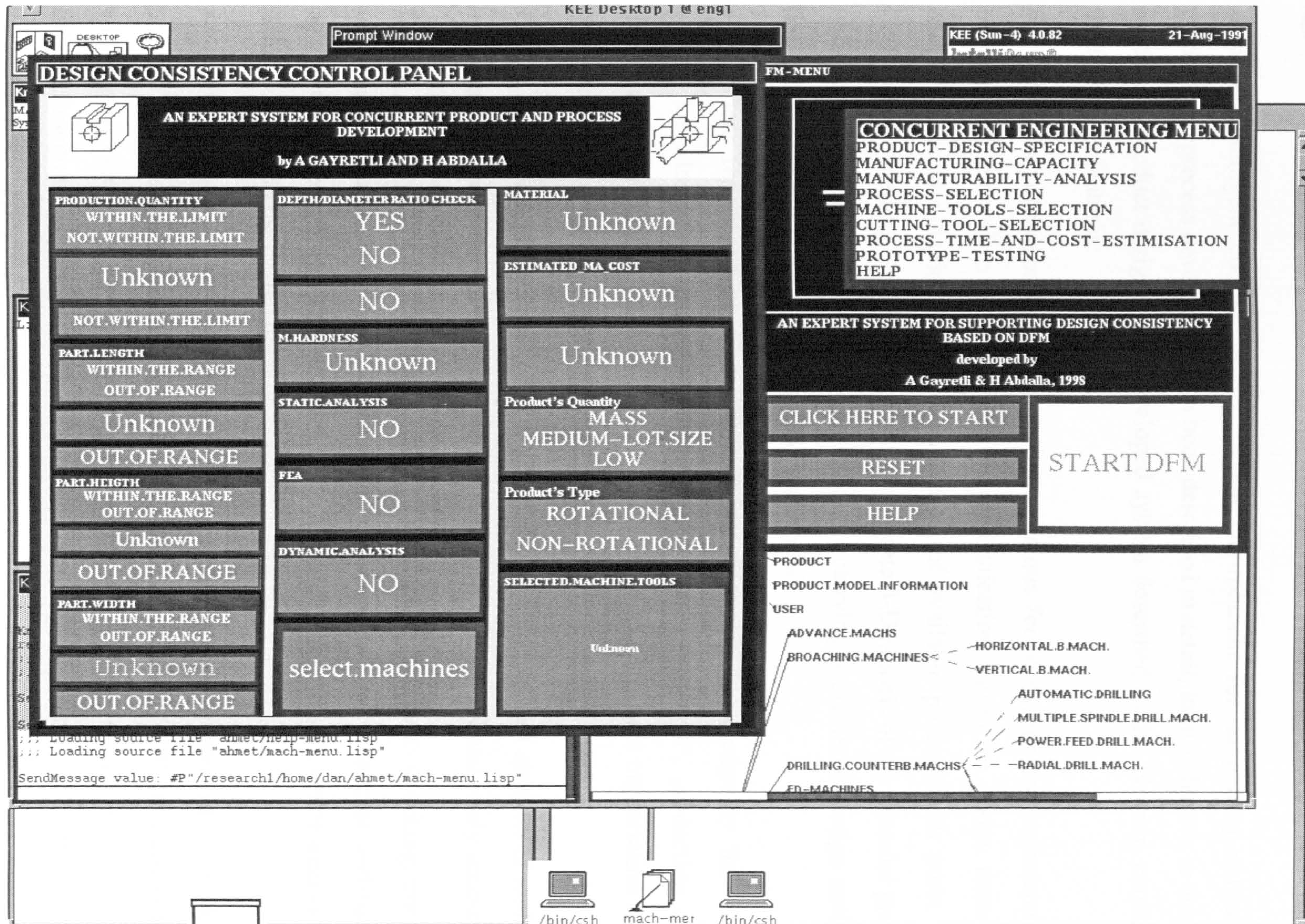


Figure 4-18 The User Interface

4.9 Summary

A novel intelligent constraint-based design environment for supporting concurrent product and process development has been described in detail, in this chapter, to achieve successful product designs. The developed system described in this chapter, contained the following features:

- Use of the feature-based representation technique for modelling and representation of parts and features to provide effective communication within the design team and simplify process planning by the consideration of available processes for parts. The CAD solid modelling, Pro/Engineer used to generate 3-D models of the intended part, to retrieve topological and geometrical attributes for carrying out different design analyses (i.e. process selection and manufacturability analysis).

- Efficient representation of design and manufacturing knowledge by the use of various knowledge representation techniques such as LISP, OOP, production rules, frames and constraints to provide flexible, updateable and effective organisation of the knowledge necessary for design analyses.

- The integration of the knowledge representation techniques and creation of multiple rule classes to make the developed system flexible and run quickly and easily accessible.

- The accomplishment of various analyses (manufacturing capacity checking, material selection, manufacturing process selection, optimisation and time/cost estimation, cutting tool selection, machine tools selection and prototype testing), which enabled the final decisions on the design quickly.

- Implementation of sets of problem solving techniques and reasoning heuristics to provide answers to queries presented by the users. The use of OOP, production rules with forward and backward chaining and combination of these techniques for problem solving. Integration of the problem solving techniques to reduce the size of rule classes, to create more powerful rule applications, made the system flexible and run more efficiently.

- The utilisation of production rules with forward chaining for search facilities and conflict resolution. The production rules with backward chaining used for user input, and OOP for conflict resolution and calculation. The combination of these techniques to enable design tasks to be accomplished in a reasonable time by reducing rule sizes and runs the system faster.

- An agent-based design consistency approach for ensuring information transferred for one area to another was consistent. It included an explanation system for reasons for conflicts and linked to the constraint-based system. Consistency in the constraint network achieved by the consistency agent responsible for dealing with conflicts. Consideration of various critical tasks (overall co-ordination, control, consistency, and data integrity) without costly-design iterations caused by conflicts.

- Providing the designers with the ability to monitor inconsistencies via the user interface. KEE objects and images attached to variables whose values to be monitored by the users to enable visual displays of violation of constraints and explanations for conflicts.

- A user-friendly interface for providing the designers with an interactive design environment. It comprised of three major elements; concurrent engineering menu for design analyses and conflict resolution, design consistency control panel for monitoring inconsistencies and typescript window for text displays on the reasons for conflicts.

As a result, the developed prototype system has the combination of the above features, which had not been incorporated into the previously-developed systems, provided a unique approach to support concurrent product development.

CHAPTER 5

5 COST ESTIMATION, PROCESS SELECTION AND OPTIMISATION

5.1 Overview

This chapter proposes a model for process selection and optimisation of mechanical components. The proposed methodology encompasses a form feature database, designer requirements, manufacturing processes and constraints, an evaluation and optimisation module and a user interface. The selection of possible manufacturing processes for a part and their evaluation and optimisation of those processes are subjected to the designer constraints. The process will also involve optimum cutting parameters and the calculation of process time and cost. A rule-based algorithm was used for process selection and optimisation.

5.2 Introduction

Concurrent engineering is a philosophy, which aims to address the consideration of different product life cycle issues in the early stages of the design process, in order to analyse the factors affecting manufacturing processes. Recently, concurrent engineering has placed greater emphasis on the automation and optimisation of manufacturing processes, as it has a major effect on product cost. There has been little research effort carried out on manufacturing cost estimation in the early stages of the design process (Ou-Yang and Lin (1997). It was pointed out that over 70% of the total product cost was incurred at the design stage (Huthwaite (1989), Ou-Yang and Lin (1997)).

Existing methodologies and tools for cost estimation, process selection and optimisation are unable to provide cost information directly to the designers (Asiedu and Gu (1998)). There are many constraints related to part features, feature-process relations, machine tools, cutting tools, cost and time in concurrent product development process. Every aspect of the product life cycle has an impact on process cost.

Therefore, the constraints of the life cycle issues also have to be involved in process evaluation and optimisation process, in order to reach a cost-effective design. Process planning aims to produce parts in accordance with the design specification with the highest possible quality, whilst at the same time taking into account economic considerations. After an optimal process plan is generated, it has to be improved in accordance with the given criteria. Process optimisation needs to be carried out at several levels of detail. At the highest level, the selection of processes, machine tools, cutting tools, etc. can be carried out. At a more detailed level, the selection of feasible cutting parameters such as feed-rate, cutting speed and depth of cut should be considered. In addition, process time and cost of processes, tools and set-up times are calculated in this level.

5.3 The Proposed Approach to Process Selection and Optimisation

The proposed model comprised a form feature database; design requirements, manufacturing processes and constraints; an evaluation and optimisation module, and a user interface as shown in Figure 5-1.

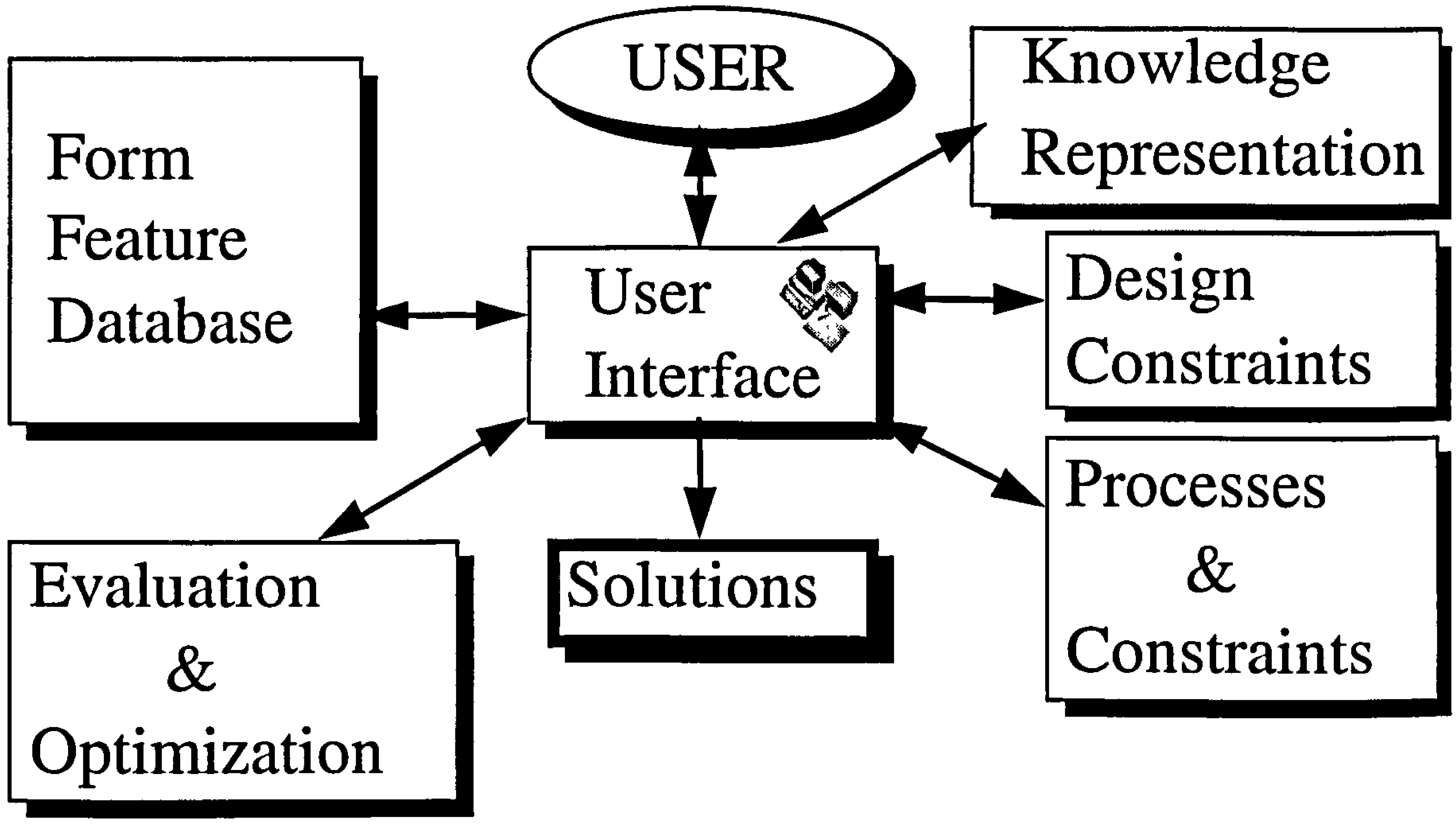


Figure 5-1 The Proposed Model for Process Selection and Optimisation

The designer communicates with each module via the user interface. His/her requirements (i.e. process time and cost, tool cost, set-up time and cost) can be entered, in the system as a set of constraints. For example, he/she can specify, to the system, that process cost, time and tool cost must not exceed the predefined values. The form feature database includes various types of form features, which are likely to be features of the part. The system retrieves manufacturing form features and parameters, from the feature database, in order to choose the feasible processes. The processes and constraints module contains manufacturing information (i.e. feature type, material, length and diameter ratio, cutting tool specifications, process availability, machines, accessibility, tolerance, surface finishes, optimum cutting parameters, cost and time). This module also includes representation of available processes and constraints, in order to evaluate and optimise the manufacturing processes of a part. Based on the manufacturing constraints, the system analyses the form features of the part, then selects the feasible processes, and calculates the process time and cost. For example, if a form feature in a part has tight tolerances, special surface finish and a complex shape, it should be machined at first on a machining centre using a special cutting tool. Then a grinding or reaming process might be used to meet the required tolerance and surface finish. Finally the system, using an algorithm, evaluates the selected processes according to criteria, provided from the design specification. It then calculates the total process time and cost of each form feature. If all the process combinations are found to be unacceptable, then the system initiates a dialogue with the user on possible modifications to the design. This process will be repeated until a set of process combinations, which satisfy the user requirements, is reached.

5.3.1 Process Selection

Process selection requires a number of criteria to be considered for each form feature. Some of the criteria are shown below:

1. Specific customer requirements:

- Maximum process time and cost,
- maximum tool cost.

2. Part:

- Type: rotational or non-rotational.
- Quantity: small, medium-lot size and mass.

3. **Manufacturing cell capacity:**

- Maximum length, diameter, weight and tolerances.

4. **Standardisation:**

- Cutting tools, tolerances and processes.

5. **Feature type:**

- Holes: through holes, blind holes, and slots, etc.
- Slots: corner radius to be same over slot, slot bottom to be parallel to the part bottom, tool radius to be same as corner radius.

6. **Material:**

- hardness and machine-ability.

7. **Sequences:**

- rough machining of faces, slots and pockets;
- drilling holes;
- counter boring and counter sinking of holes;
- threading of holes and reaming holes;
- chamfering and filleting of holes;
- finish machining of slots, steps, pockets;
- finish machining of faces;
- chamfering and filleting of corner.

8. **Length and diameter ratio:**

- 8/1 for twist drilling, 5/1 for boring, and 20/1 for EDM.

9. **Availability of machines, processes and cutting tools:**

- YES/NO from user.

10. **Tolerance:**

- broaching ±0.025 mm and boring ±0.04 mm.

11. **Surface finishes:**

- drilling 1.6-6.3μm and reaming 0.8-3.2 μm.

A flowchart for process selection for form features of the component and some of the results for the selection of the possible machining processes are shown in Figure 5-2 and 5-3. These possible processes will be evaluated in order to select most feasible processes for the component, based on the optimisation approach shown in Figure 5-4.

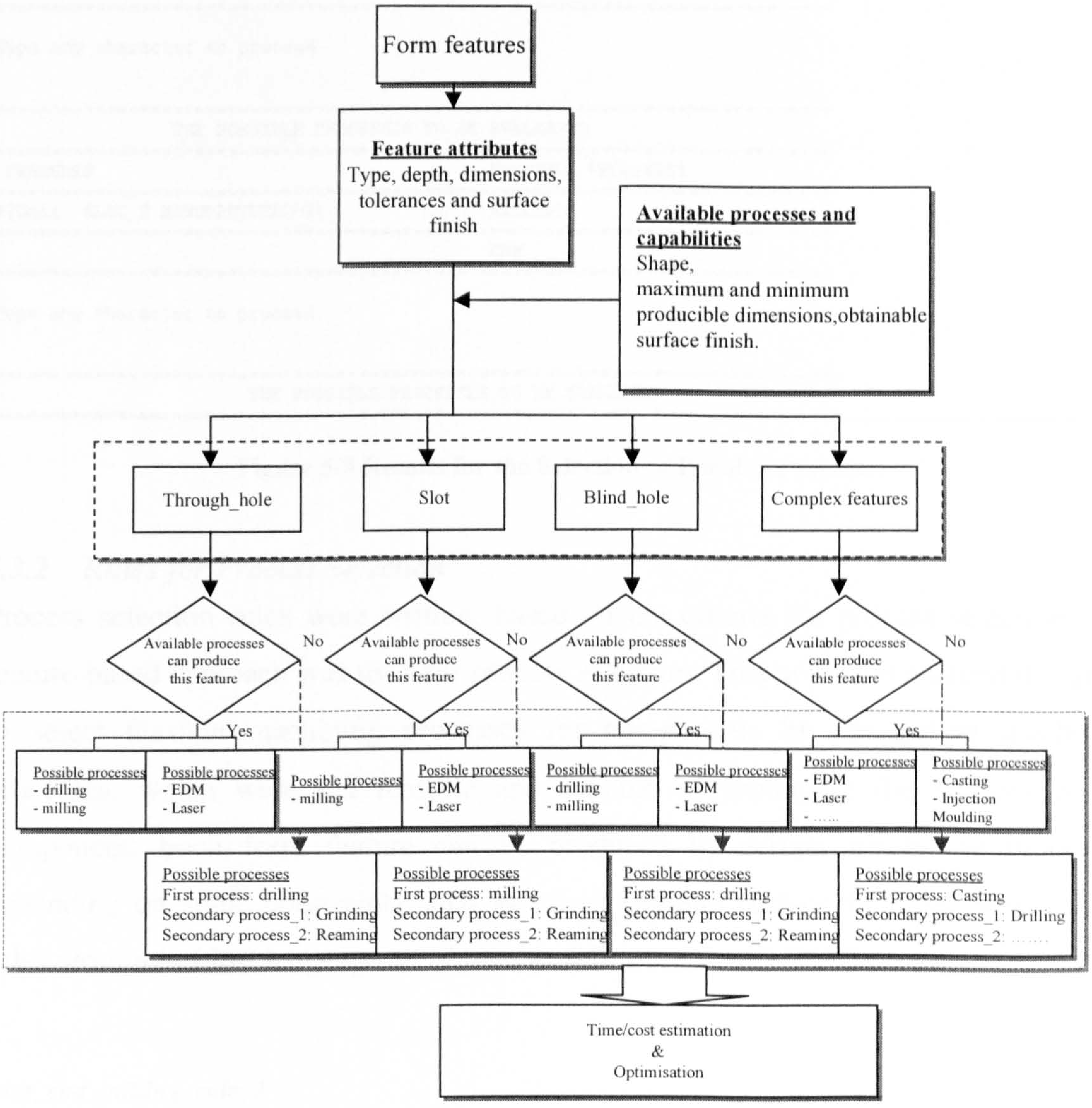


Figure 5-2 Flowchart for Process Selection

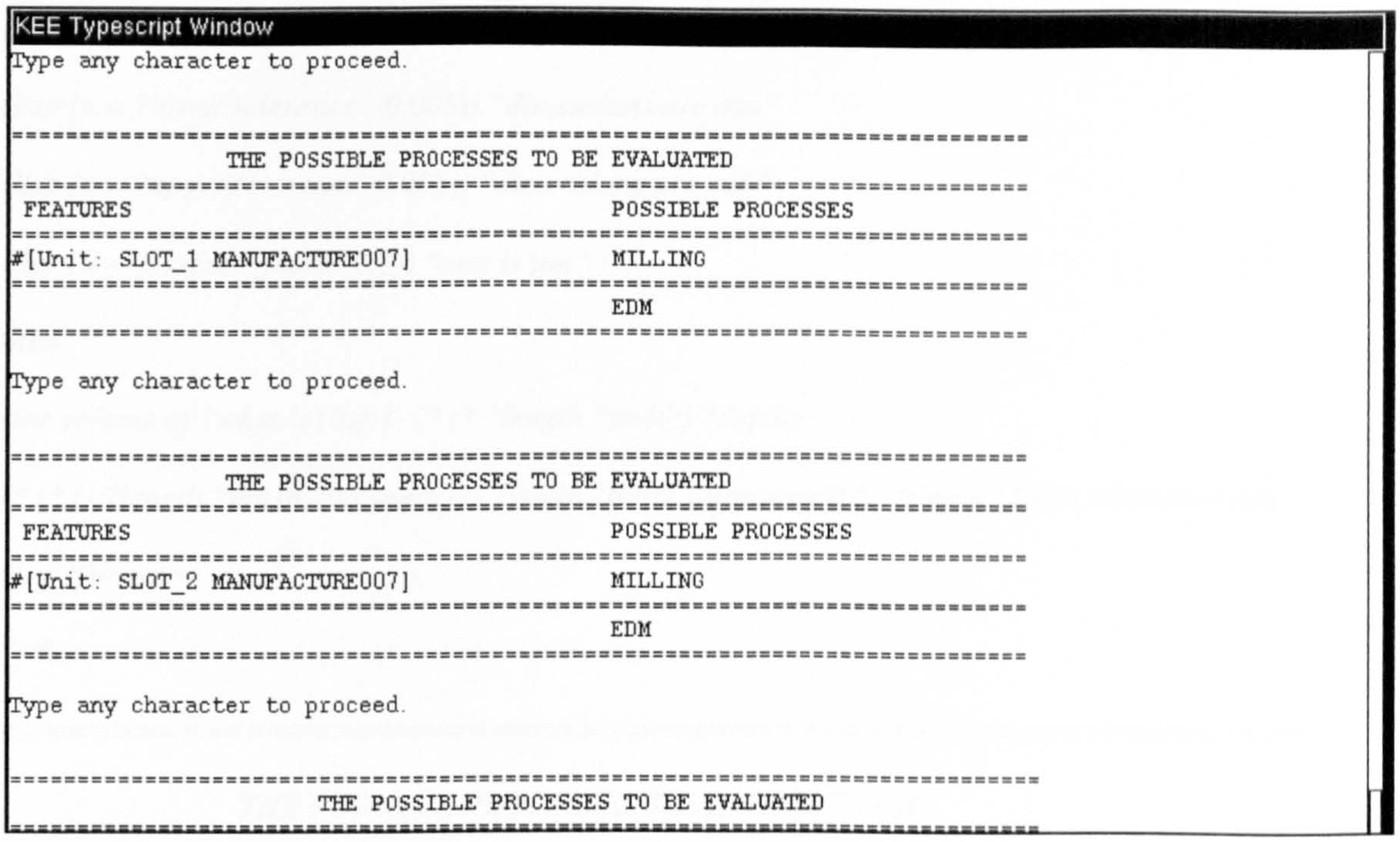


Figure 5-3 Results for the Selection of Possible Processes

5.3.2 Rules for Process Selection

Process selection rules were written, based on the criteria for process selection. The feature-based approach was used for process selection. This approach enabled designers to select feasible machining processes for components by eliminating machining processes, which were not feasible and capable of producing the features of the component. Each form feature can be produced by certain machining processes, depending on some constraints such as tolerances and surface finishes. Some of the rules written in LISP language are shown as follows.

(slot_end_milling_rule_1

*(**if** (?what is in block-slot)*

(the length of ?what is ?length)

(the width of ?what is ?width)

(the depth of ?what is ?depth)

(the finish.allowance of ?what is ?finish.allowance)

(the lower.tolerance of ?what is ?lower.tolerance)

(the upper.tolerance of ?what is ?upper.tolerance)

```
(the surface_finish of ?what is ?surface_finish)

(lisp (<= ?lower.tolerance  -0.005)) "dimensions are mm"

(lisp (>= ?upper.tolerance  0.005)) "dimensions are mm"

(lisp (>= ?surface_finish  0.8)) "unit is µm"

then

(the volume of ?what is (lisp (- (* (* ?length ?width) ?depth)

(* (* (- ?length ?finish.allowance) (- ?width ?finish.allowance)) ( - ?depth ?finish.allowance)))))

(lisp (format t

"~%

==================================================================

                    THE POSSIBLE PROCESSES TO BE EVALUATED

==================================================================

FEATURES                                              POSSIBLE PROCESSES

==================================================================

~D                                                    MILLING

==================================================================

                                                      EDM

==================================================================~%"

?what))

(the first.process.selection of ?what is ok)

(the possible.process_1 of ?what is milling)

(the possible.process_2 of ?what is EDM)))

(slot_end_milling_rule_2

(if (?what is in block-slot)

(not (the first.process.selection of ?what is ok))

(the length of ?what is ?length)

(the width of ?what is ?width)

(the depth of ?what is ?depth)
```

(the finish.allowance of ?what is ?finish.allowance)

(the lower.tolerance of ?what is ?lower.tolerance)

(the upper.tolerance of ?what is ?upper.tolerance)

(the surface_finish of ?what is ?surface_finish)

then

(the volume of ?what is (lisp (- ((* ?length ?width) ?depth)*

((* (- ?length ?finish.allowance) (- ?width ?finish.allowance))*

(- ?depth ?finish.allowance)))))

(the possible.process_1 of ?what is milling)

(the secondary.process of ?what is grinding)))

5.3.3 *Process Evaluation*

The material, to be used to produce the part, has an important effect on the selection of the machining parameters such as tool material, cutting speed, feed rate, and tool geometry. These machining parameters can be obtained from various machinery handbooks (i.e. Machining Data Handbook, 1980) and cutting tool manufacturers data sheets and databases. The cost data, used in the estimation of direct labour cost was obtained from a car manufacturer in East Midland. Information about set-up times for various machine tools, cutting tools cost data, operations and manufacturing technologies was available in various handbooks such as the AM Cost Estimator/Cost Estimation Database (Ostwald, 1988), tool manufacturers' catalogues and machinery handbooks. They were also used to consider the parameters and specification of machining tools (i.e. set-up times, time to stop and start machines, cutting tools, and fixtures). Figure 5-4 shows the proposed model for the selection and evaluation of manufacturing processes.

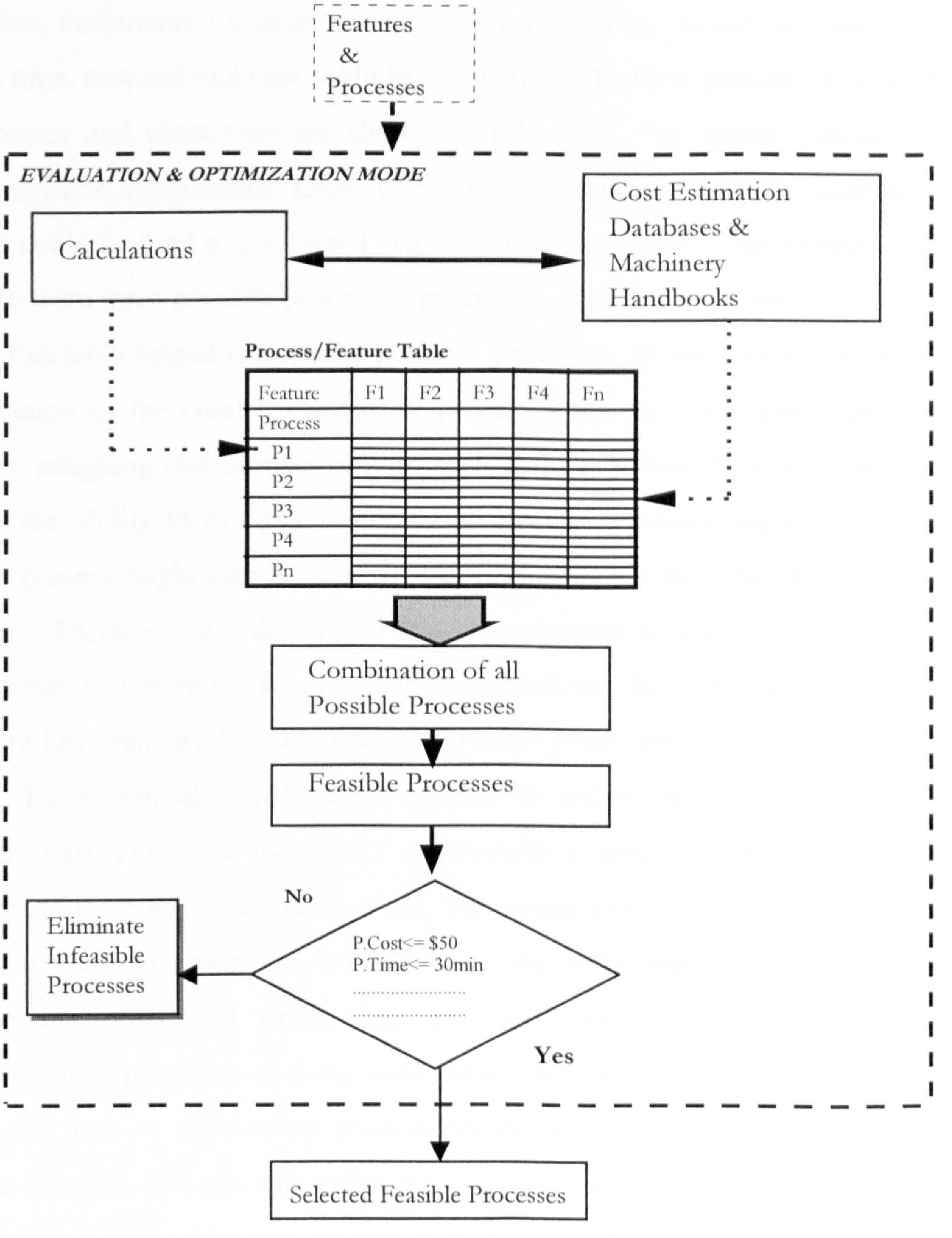


Figure 5-4 The Optimisation Approach

Process optimisation was defined as the reduction of the total process time and cost based on process variables (i.e. cutting speed, feed-rate, cutting force, power, and surface finish constraints) (Chang and Wysk, 1985). A table was generated to consider form features, select possible processes for each feature and the criteria for the optimisation and evaluation of the processes.

Using this table, constraints for processes of each form feature, based on their input about process time, cost and tool cost could be considered. The form features of the part, possible processes and constraints are shown in Table 5-1. The system carried out process time and cost calculations. Each form feature was matched with a number of processes that could be used to produce it. This is shown in Table 1. For example, for feature_1 there were three possible processes, process_1, process_3 and process_n. The generation of this table helped to consider possible processes, for each form feature, so that the evaluation of the combination of all processes for the component could be carried out, by assigning one process only to each feature in turn. This provided the designer with the ability to evaluate hundreds of process combinations for the part. However, this process might take a lot of time to find available and feasible processes for each feature. Therefore, in order to find feasible processes in reasonable amount of time, the processes that were not feasible, had to be excluded from the table. The rule-based algorithm has been developed to deal with this problem, and will be presented in later sections. The system also enabled the designer to define maximum process cost and time for the part. This made the system very flexible to keep total process cost and time of the part to the predefined values. Then, the system evaluated the set of process combinations or possible processes, for machining the form features of the part, by comparing process costs and times, and the other variables against the user requirements. Feasible processes were the ones, which met the user requirements. It was possible to select one of the feasible process combinations as a solution or further evaluation was possible. Specific constraints (i.e. process cost and time) could be altered to obtain a feasible solution to satisfy the user requirements. Maximum process time and cost could be changed by the designer to obtain a feasible set of process combination if necessary. In addition, The user interface informed the user of the results of the process selection and optimisation (Figure 5-5).

```
KEE Typescript Window
                 THE RESULTS OF PROCESSES EVALUATION AND COST-TIME FIGURES
==========================================================================================
FEATURE                                      TIME (min/unit)      COST(£) / 100 unit
==========================================================================================
  #[Unit: SLOT_2 MANUFACTURE007]
==========================================================================================
MACHINING PROCESS             EDM           3.12                  264.87
==========================================================================================
                             MILLING        0.16                   58.66
==========================================================================================

Type any character to proceed.
Type any character to proceed.

>>>>> THE FEASIBLE PROCESS OF #[Unit: SLOT_2 MANUFACTURE007]  IS END.MILLING AND
 ITS COST IS £58.66..

Type any character to proceed.
Type any character to proceed.
Type any character to proceed.

==========================================================================================
                 THE RESULTS OF PROCESSES EVALUATION AND COST-TIME FIGURES
==========================================================================================
FEATURE                                      TIME (min/unit)      COST(£) / 100 unit
==========================================================================================
  #[Unit: SLOT_1 MANUFACTURE007]
==========================================================================================
MACHINING PROCESS             EDM          3.12                   264.87
==========================================================================================
                             MILLING       0.16                    58.66
==========================================================================================

Type any character to proceed.
Type any character to proceed.

>>>>> THE FEASIBLE PROCESS OF #[Unit: SLOT_1 MANUFACTURE007]  IS END.MILLING AND
 ITS COST IS £58.66..

Type any character to proceed.
Type any character to proceed.

==========================================================================================
                 THE RESULTS OF PROCESSES EVALUATION AND COST-TIME FIGURES
==========================================================================================
FEATURE                                          TIME(min/unit)          COST(£) / 100 unit
==========================================================================================
```

Figure 5-5 Results of Process Optimisation

Processes \ Features		Feature_1	Feature_2	Feature_3	Feature_n
Process_1	Process Time	T_{11}	....		T_{1n}
	Process Cost	C_{11}	....		C_{1n}
	Tool cost	TC_{11}	....		TC_{1n}
	Accessibility	A_{11}	....		A_{1n}
	Tolerance	T_{11}	....		T_{1n}
	....	....	....		....
Process_2	Process Time		....	T_{23}	
	Process Cost		....	T_{23}	
	Tool cost		....	TC_{23}	
	Accessibility		....	....	
	Tolerance		....	....	
	....		....	....	
Process_3	Process Time	....		....	....
	Process Cost	....		....	....
	Tool cost	....		....	....
	Accessibility			....	....
	Tolerance			....	....
	....	....		....	....
Process_4	Process Time		....	....	
	Process Cost		....	....	
	Tool cost		....	....	
	Accessibility		....	....	
	Tolerance		....	....	
	....		....	....	
Process_m	Process Time	T_{m1}			....
	Process Cost	C_{m1}			....
	Tool cost	TC_{m1}			....
	Accessibility	A_{m1}			....
	Tolerance	T_{m1}			....
	....	....			....

Table 5-1 Process-Feature Table for Optimisation of Machining Processes for the Part

5.3.4 Process Time and Cost Estimation

Process time was calculated using standard formulae. As the proposed approach was based on feature-based cost estimation and optimisation of manufacturing processes, the following formula was used to estimate process time.

$$\text{Process time} = \frac{\text{Form feature volume}}{\text{Material removal rate}} \qquad (1)$$

Form feature volumes are calculated using standard formulae. Material removal rate differed from one process to another, depending on tool diameter and type, type of material, and cutting parameters. Some of the manufacturing processes and material removal rate are shown in Table 5-2.

Process	Machining time	Spindle power	Tool life	Material Removal	Form feature volume(Fv)
Drilling	$2(l_{max}/V_f)k + 2l/V_f$	$T N/63030\eta_m$	-	$(\pi Dt^2 / 4) f N$	$\pi D^2 / 4 h$
Rough milling	Fv / MRR	$F_c V_c/33{,}000\ \eta_m$	$C / V^{\alpha} f^{\beta} a_p \gamma$	$W a_p f n N$	Feature volume
Finish milling	$Surf/V_f \Omega$	$F_c V_c/33{,}000\ \eta_m$	-	$W a_p f n N$	Feature volume
Grinding	$LT_s Dia/(WiP)2f_i \pi V_g$	-	-	π f Dia P	Feature volume

Table 5-2 Formula for Estimation of Process Related Concerns (Chang, 1990)

Definitions:

l_{max}: maximum drilling depth T_s: total stock removed from the diameter *f*, V_f: feed-rate N: spindle rpm k: index for number of drilling cycles *D*: diameter *Dt:* tool diameter Fv: feature volume l: length of hole to be drilled η_m: machine efficiency *h*: depth MRR: material removal rate F_c: cutting force *C*: a constant determined by geometry of hole, tool material and part material *V:* cutting speed a_p: depth of cut, inch. γ, α, β: coefficients *W:* width of cutter *n:* number of teeth *L:* length of the part grind *T:* torque *Dia*: original diameter *Wi*: width of the grinding wheel *P*: traverse for each work revolution in fraction of wheel width f_i: infeed of wheel per pass V_g: workpiece peripheral velocity Surf: feature surface Ω: overlapping factor, cutting depth for circumferential-milling and width of cut for face milling

In order to reduce process time, material removal rate (MRR) should be maximised subject to;

$T_l = T_{lmax}$ (Tool life)

$f = f_{max}$ (Feed-rate)

$V = V_{max}$ (Speed)

$W = W_{max}$ (Depth of cut)

Cutting parameters such as feed-rate, spindle speed and depth of cut had to be optimum. The consideration of selected material attributes such as hardness, machinability, compressive strength and electrical conductivity has a major effect on cutting parameters.

Having chosen suitable cutting tools, that meet the material requirements, MRR for any processes can be estimated by using the related formulas. Then the process time, for manufacturing the form features of the part, can be calculated. Process cost estimation was carried out using the estimated process time. Productive Hour Cost (direct labour cost), which was £ 24.32 per hour was obtained from a company in East Midland in order to estimate process costs. Using the company's data, total process cost was calculated as follows:

$$\text{Total process cost} = \text{Lot} - \text{time} * \text{Direct Labour Cost (PHC)}$$

Lot-time was based on the quantity of part or a form feature. The total cost can be formulated as follows:

$$\text{Total cost} = \text{MaterialCost} + \sum[(\text{Lot-time} * \text{PHC}) + \text{Tool Cost} + \text{SetupCost}] \quad (3)$$

Set-up times for various machine tools, included in the machining handbook were used to estimate set-up costs to reach a more accurate cost estimation (Bralla, 1986; Machining Data Handbook, 1980, and AM Cost Estimator, 1988). Figure 5-6 shows some results for time/cost estimation of the possible machining processes for the features of a component.

```
KEE Typescript Window
==========================================================================================
                 THE RESULTS OF PROCESSES EVALUATION AND COST-TIME FIGURES
==========================================================================================
FEATURE                                  TIME(min/unit)         COST(£) / 100 unit
==========================================================================================
#[Unit: T_HOLE_2 MANUFACTURE007]
==========================================================================================
MACHINING PROCESSES      DRILLING        0.23                   26.85
==========================================================================================
                         EDM             0.80                   76.95
==========================================================================================
                         MILLING         0.16                   21.06
==========================================================================================

Type any character to proceed.
Type any character to proceed.
Type any character to proceed.
Type any character to proceed.

==========================================================================================
                 THE RESULTS OF PROCESSES EVALUATION AND COST-TIME FIGURES
==========================================================================================
FEATURE                                  TIME(min/unit)            COST(£) / 100 unit
==========================================================================================
#[Unit: T_HOLE_3 MANUFACTURE007]           0.23                      26.85
==========================================================================================
MACHINING PROCESSES      DRILLING          0.80                      76.95
==========================================================================================
                         EDM               0.16                      21.06
==========================================================================================
                         MILLING
==========================================================================================

Type any character to proceed.
Type any character to proceed.
Type any character to proceed.
Type any character to proceed.

==========================================================================================
                 THE RESULTS OF PROCESSES EVALUATION AND COST-TIME FIGURES
==========================================================================================
FEATURE                                  TIME(min/unit)          COST(£) / 100 unit
==========================================================================================
#[Unit: T_HOLE_4 MANUFACTURE007]
==========================================================================================
MACHINING PROCESSES      DRILLING        0.23                   26.85
==========================================================================================
                         EDM             0.80                   76.95
==========================================================================================
                         MILLING         0.16                   21.06
==========================================================================================

Type any character to proceed.
```

Figure 5-6 Time/Cost Estimation of the Possible Processes

5.3.5 The Process Optimisation Scenario

Manufacturing processes should be optimised following a detailed manufacturability analysis of the manufacturing cell capability, production quantity, available processes and their constraints, feature types, dimensions and tolerances. The rule-based algorithm for optimisation of manufacturing processes is presented below. It consists of two main steps; process selection, and optimisation. Steps 1-4 involve the selection of feasible processes for each form feature based on material, lot-size, tolerance, surface finish, and feature type. The next step contains suitable cutting tool selection, machine tools selection, selection of optimum cutting parameters, calculations of process variables such as material removal rate (MRR), lot time, set-up cost, and tool cost. In addition, the comparison of selected processes based on the process variables was carried out. Figure 5-7 shows the various steps and tasks involved in the process optimisation.

1. Select a material from the database
2. Obtain lot-size of part or features
3. Obtain a form feature from the part
4. Select feasible processes for the feature satisfying requirements of the part (tolerance, surface finish, feature type, etc.)
5. Select one of the possible processes
6. Select the largest possible diameter, shortest length, and available and cost effective cutting tools for the selected process
7. Select available machine tools and fixtures
8. Select optimum cutting parameters; depth of cut, cutting speed, feed-rate and cooling conditions.
9. Calculate the feature volume, MRR, lot-time, tool cost for the lot-size, set-up cost for the process.
10. Calculate total cost and time of the process
11. If there are possible processes left to be analysed go to 5 else go to 12
12. Compare the possible processes for each form feature with each other and eliminate the processes which has higher tool, process and set-up cost and time value than others

13. If there is only one process for the form feature consider it to be the most feasible process else ask user to select one process from the list
14. If there are form features left to be analysed go to 3 else 15
15. Calculate final process cost of the part
16. Inform the user
17. End

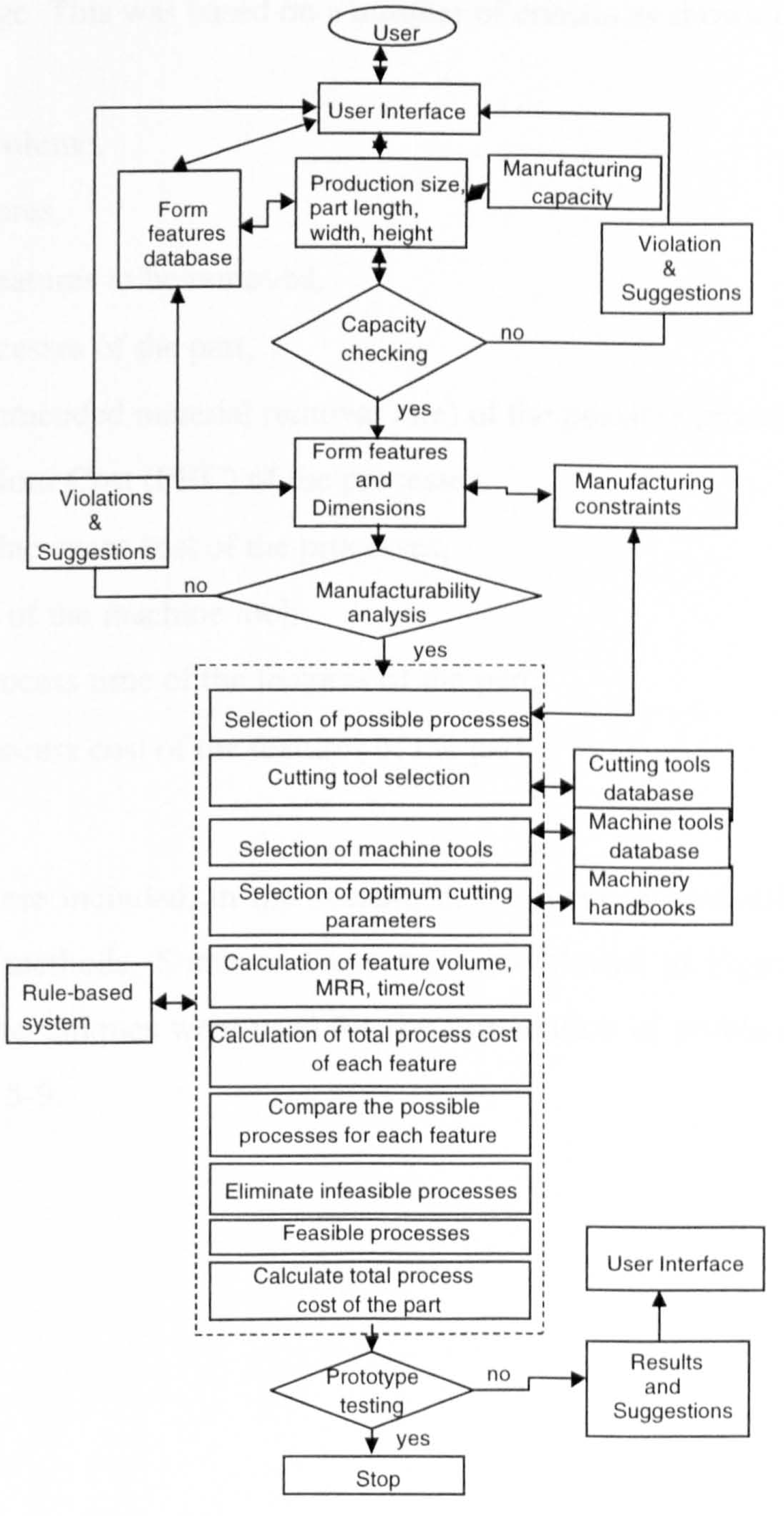


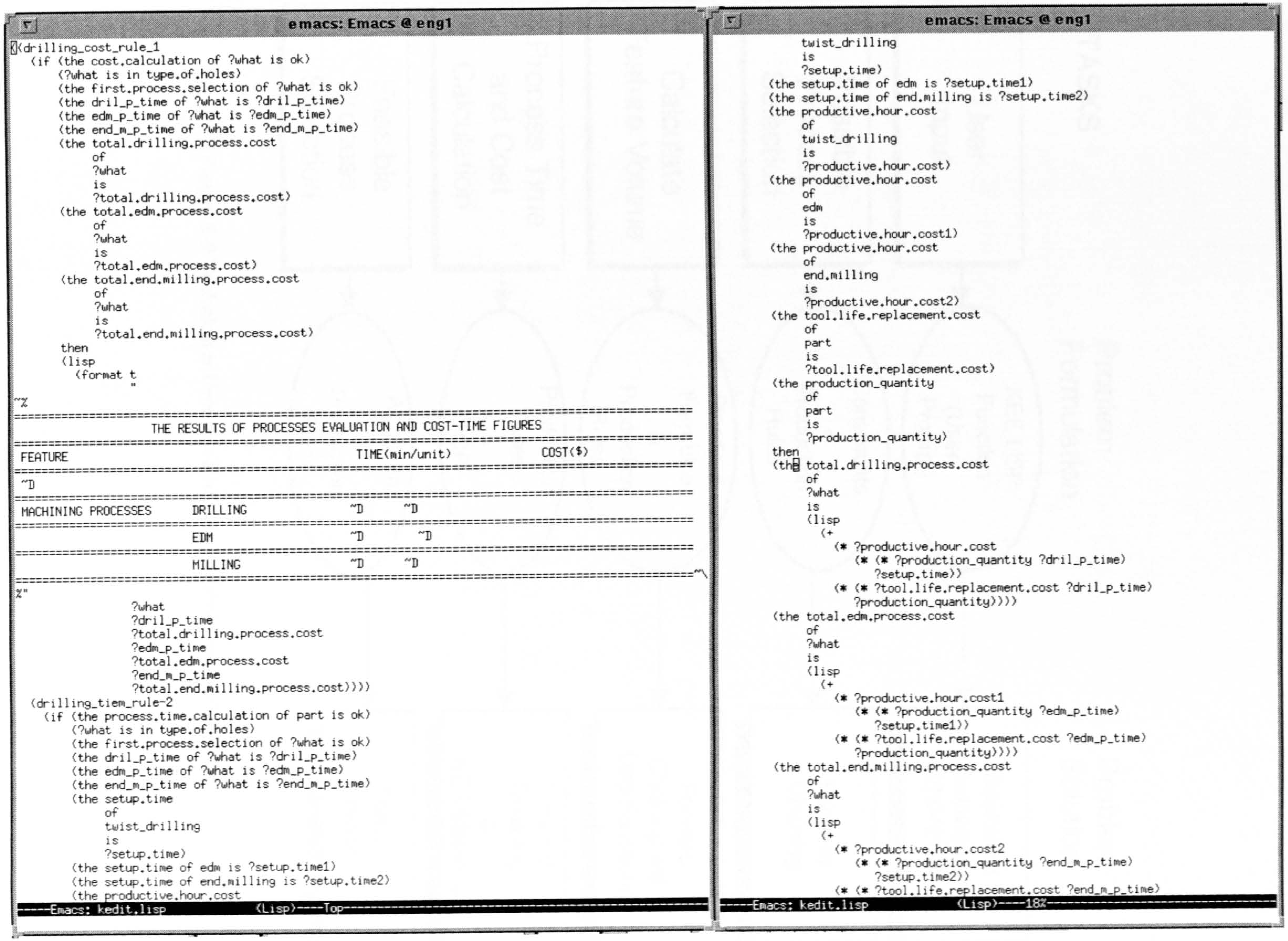
Figure 5-7 Various Steps Involved In The Manufacturing Process Optimisation

5.3.6 *Rules for Time/Cost Estimation and Process Optimisation*

The production rules for time/cost estimation and process optimisation were written in the LISP language. This was based on a number of criteria as shown below:

- Production volume,
- Type of features,
- Volume of features to be removed,
- Possible processes of the part,
- MRR (recommended material removal rate) of the possible processes,
- Productive Hour Cost (PHC) of the processes,
- Tool life replacement cost of the processes,
- Set-up times of the machine tools,
- Estimated process time of the features of the part,
- Estimated process cost of the features of the part.

These criteria were included, in the system, in the form of production rules including constraints and methods. Some of these rules are shown in Figure 5-8. In the rule classes, various techniques were used for the formulation of problems and solutions as shown in Figure 5-9.



emacs: Emacs @ eng1

```
(drilling_cost_rule_1
  (if (the cost.calculation of ?what is ok)
      (?what is in type.of.holes)
      (the first.process.selection of ?what is ok)
      (the dril_p_time of ?what is ?dril_p_time)
      (the edm_p_time of ?what is ?edm_p_time)
      (the end_m_p_time of ?what is ?end_m_p_time)
      (the total.drilling.process.cost
           of
           ?what
           is
           ?total.drilling.process.cost)
      (the total.edm.process.cost
           of
           ?what
           is
           ?total.edm.process.cost)
      (the total.end.milling.process.cost
           of
           ?what
           is
           ?total.end.milling.process.cost)
      then
      (lisp
        (format t
           "
~%
==========================================================================
                THE RESULTS OF PROCESSES EVALUATION AND COST-TIME FIGURES
==========================================================================
FEATURE                                          TIME(min/unit)        COST($)
==========================================================================
~D
==========================================================================
MACHINING PROCESSES       DRILLING               ~D       ~D
==========================================================================
                          EDM                    ~D        ~D
==========================================================================
                          MILLING                ~D       ~D
==========================================================================~\
%"
                 ?what
                 ?dril_p_time
                 ?total.drilling.process.cost
                 ?edm_p_time
                 ?total.edm.process.cost
                 ?end_m_p_time
                 ?total.end.milling.process.cost))))
  (drilling_tiem_rule-2
    (if (the process.time.calculation of part is ok)
        (?what is in type.of.holes)
        (the first.process.selection of ?what is ok)
        (the dril_p_time of ?what is ?dril_p_time)
        (the edm_p_time of ?what is ?edm_p_time)
        (the end_m_p_time of ?what is ?end_m_p_time)
        (the setup.time
             of
             twist_drilling
             is
             ?setup.time)
        (the setup.time of edm is ?setup.time1)
        (the setup.time of end.milling is ?setup.time2)
        (the productive.hour.cost
----Emacs: kedit.lisp          (Lisp)----Top----------------------------------
```

emacs: Emacs @ eng1

```
             twist_drilling
             is
             ?setup.time)
        (the setup.time of edm is ?setup.time1)
        (the setup.time of end.milling is ?setup.time2)
        (the productive.hour.cost
             of
             twist_drilling
             is
             ?productive.hour.cost)
        (the productive.hour.cost
             of
             edm
             is
             ?productive.hour.cost1)
        (the productive.hour.cost
             of
             end.milling
             is
             ?productive.hour.cost2)
        (the tool.life.replacement.cost
             of
             part
             is
             ?tool.life.replacement.cost)
        (the production_quantity
             of
             part
             is
             ?production_quantity)
        then
        (the total.drilling.process.cost
             of
             ?what
             is
             (lisp
               (+
                 (* ?productive.hour.cost
                    (* (* ?production_quantity ?dril_p_time)
                       ?setup.time))
                 (* (* ?tool.life.replacement.cost ?dril_p_time)
                    ?production_quantity))))
        (the total.edm.process.cost
             of
             ?what
             is
             (lisp
               (+
                 (* ?productive.hour.cost1
                    (* (* ?production_quantity ?edm_p_time)
                       ?setup.time1))
                 (* (* ?tool.life.replacement.cost ?edm_p_time)
                    ?production_quantity))))
        (the total.end.milling.process.cost
             of
             ?what
             is
             (lisp
               (+
                 (* ?productive.hour.cost2
                    (* (* ?production_quantity ?end_m_p_time)
                       ?setup.time2))
                 (* (* ?tool.life.replacement.cost ?end_m_p_time)
----Emacs: kedit.lisp          (Lisp)----18%----------------------------------
```

Figure 5-8 Rules for Time/Cost Estimation and Process Optimisation

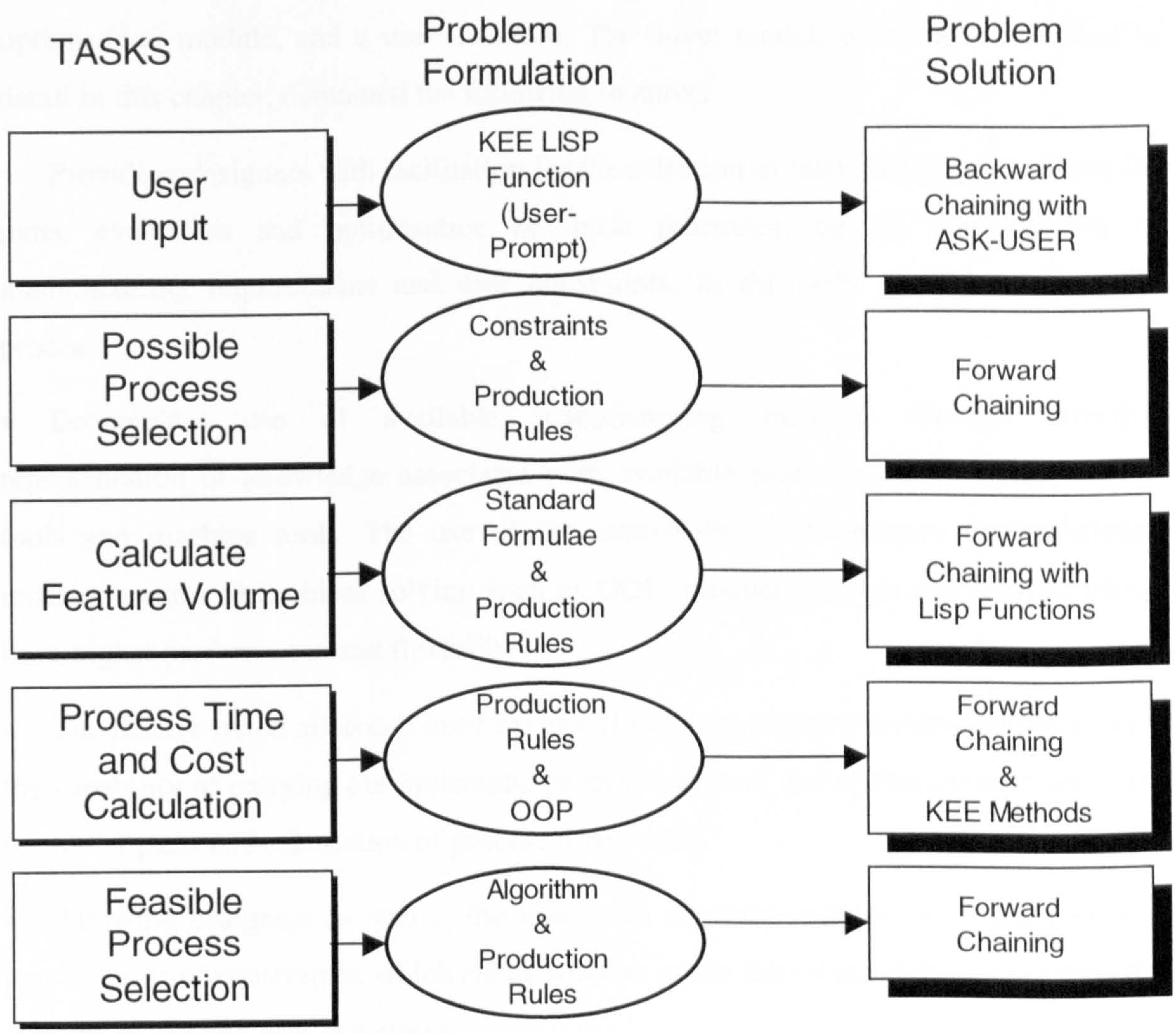


Figure 5-9 Techniques Used for Problem Formulation and Solution

5.4 Conclusion

A new model for the evaluation and optimisation of manufacturing processes has been demonstrated in detail in this chapter. The system comprised of a form feature database, designer requirements, manufacturing processes and constraints, an evaluation and optimisation module, and a user interface. The novel model, which was described in detail in this chapter, contained the following features:

- Providing designers with facilitation for the selection of manufacturing processes for parts, evaluation and optimisation of those processes, by the consideration of manufacturing requirements and user constraints, in the early stages of the design process.

- Economical use of available manufacturing facilities through effective representation of knowledge associated with available processes, capabilities, cutting tools and machine tools. The use of the state-of-the-art techniques for knowledge representation and problem solving such as OOP, production rules and frames, which have higher performance and flexibility.

- The feature-based approach used for model building, which provided designers with the capability of carrying out systematic process selection and optimisation of the form feature of parts and calculation of process times/costs.

- Allowing designers to restrict the maximum allowable process time and cost of a part in terms of constraints, which check whether or not the intended design satisfied the manufacturing and user constraints.

- A rule-based algorithm linked to the actual system for the estimation and optimisation of manufacturing processes, which enabled rapid selection of feasible machining processes, subject to criteria such as tolerance and surface finishes, which might eliminate processes, which were not feasible, not available or incapable of making features of a part.

- Allowing each form feature to be produced by certain machining processes, depending on criteria such as availability of processes, feature type, depth and diameter ratio, tolerances, surface finishes, and accessibility to reduce the computation time and provide designers with quick results.

- Allowing designer to change constraints (i.e. process cost and time) to obtain a feasible solution unless any process combinations, which satisfied the user requirements.

- The selection and evaluation of possible processes for machining the form features of the part by comparing process cost and time, and the other variables against the predefined requirements.

- A feature-process table was used for the consideration of constraints for processes of each form feature, which was based on their input on process times, costs, and tool costs.

- A process cost model for the manufacturing processes described in detail in order to optimise the selected processes subject to criteria (time and cost).

- Providing designers with the complete results of process selection and optimisation via the user interface.

As a result, this model included a combination of the above features, which had not been applied by previous research and provided a unique approach for the evaluation and optimisation of manufacturing processes.

CHAPTER 6

6 THE IMPLEMENTATION OF THE DEVELOPED PROTOTYPE CONSTRAINT-BASED DESIGN SYSTEM

6.1 Overview

This chapter presents the implementation of the developed prototype system for design for manufacture. The concurrent design of a component was carried out to illustrate the actual working of the constraint-based design environment. It assisted in the design of a product, which can be manufactured with the existing manufacturing facilities and satisfies various life cycle requirements, which were represented in the form of constraints in the knowledge base.

It was shown in the design analyses, how the developed system helped designers deal with conflicts arising from different design areas, through the design consistency management for avoiding costly design iterations, which could increase product lead time and cost. Also, the developed process optimisation module, which provided designers with the ability to estimate process cost and time, and select the most feasible machining processes for the component subject to the estimated process time and cost, and the predefined constraints is presented in this chapter. In addition, it was demonstrated that the developed system provided designers with feedback on various design analyses including material selection, manufacturing capacity checking, manufacturability analysis, process selection, cutting tool selection, machine selection, time/cost estimation and finally prototype testing.

6.2 Choice of Domain

Concurrent product and process design of a cylinder head was the domain selected for implementing the proposed constraint-based design system for automotive components. Cylinder heads are important automotive components that are used for housing different parts and act as a heat sink. These parts can be made from cast iron and aluminium alloys.

General characteristics of the components, made from cast iron, were determined in order to ensure their manufacturability with the existing manufacturing facilities. Some examples of the general characteristics of components were;

- Finish allowance of the features, to be machined, for the casting was 3 mm.
- Maximum dimensions of the components (See Appendix 1).
- Maximum and minimum diameters of the holes (See Appendix 1).

These characteristics had an important impact on the manufacturability of the components and had to be consistent with the capability of the available machines. As a result, the components could be manufactured at the lowest possible machining cost.

6.3 The User Interface of The Developed Design Environment

The developed design environment was built on a Spark Sun Workstation using the general capabilities of a knowledge-base system, KEE (Knowledge Engineering Environment. The user interface is shown in Figure 4-18. The user interacts with the design environment via keyboard input or from options on a multiple choice menu, using a special mouse. As explained in chapter 4, the user interface consisted of three main regions. The region entitled Concurrent Engineering Menu enabled designers to load necessary files automatically and carry out various design tasks easily. The region entitled Design Consistency Control Panel includes various intelligent images showing inconsistencies, which arise from different design areas, to the designer. The region, "Typescript Window" provides the designers with feedback on reasons for conflicts, analyses results, suggestions for conflict resolution, and a prompt where at the designer has to type answers and queries. The designer's primary task of interaction with the developed system is by creating components, establishing constraints and entering to the knowledge-base and modifying the design of a component subject to the suggestions given by the system.

6.4 Demonstration of The Intelligent Constraint-Based Design Environment

The developed system was evaluated through the concurrent design of a cylinder head. An example of how the constraint-based design environment could be used to provide feedback to designers about various design tasks and conflicts existed between them are presented in this section. The activities of the concurrent product development were described and examples of how conflicts arose from different design domains and how the developed system assisted the designer in solving those conflicts are presented.

6.4.1 Creating a Part Design

A 3-D solid model of the actual component was generated on a CAD system (in this case study, Pro/Engineer). This is shown in Figure 6-1. The component in Figure 6-1 was at an intermediate stage, where the actual shape of the component was determined. However, whether the component could be economically producible with the available manufacturing facilities has not yet been considered. This means that the developed constraint-based design environment enabled the designer to interact with all stages of the design process. The designer began the product design process by entering the topological and geometrical attributes of the design model into the system. The attributes of the component were automatically created in the knowledge-base and shown in the user interface. Agents were given direct access to these attributes in the knowledge-base whenever necessary. This provided the designers with the ability to make modifications on the component's attributes, subject to suggestions which were provided by the system. Therefore, consistency between the part specification and the available manufacturing facilities could be achieved. There were certain steps for carrying out these tasks and these are shown in Figure 6-2. The design specification, that included various requirements from different life cycle perspectives, had to be prepared in order to achieve concurrency between design domains. Given the design specification and available manufacturing facilities, the analysis of the component was carried out by the system.

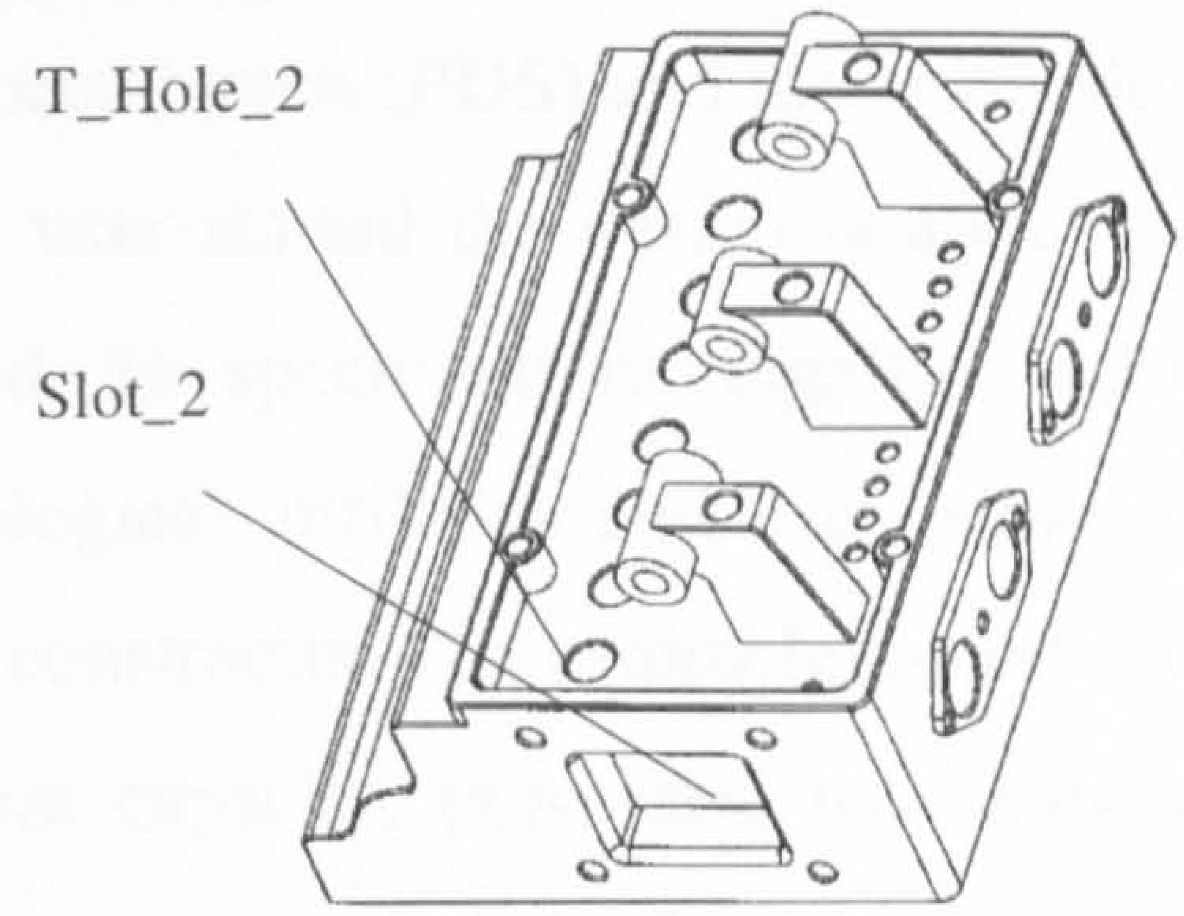


Figure 6-1 A 3-D Solid Model

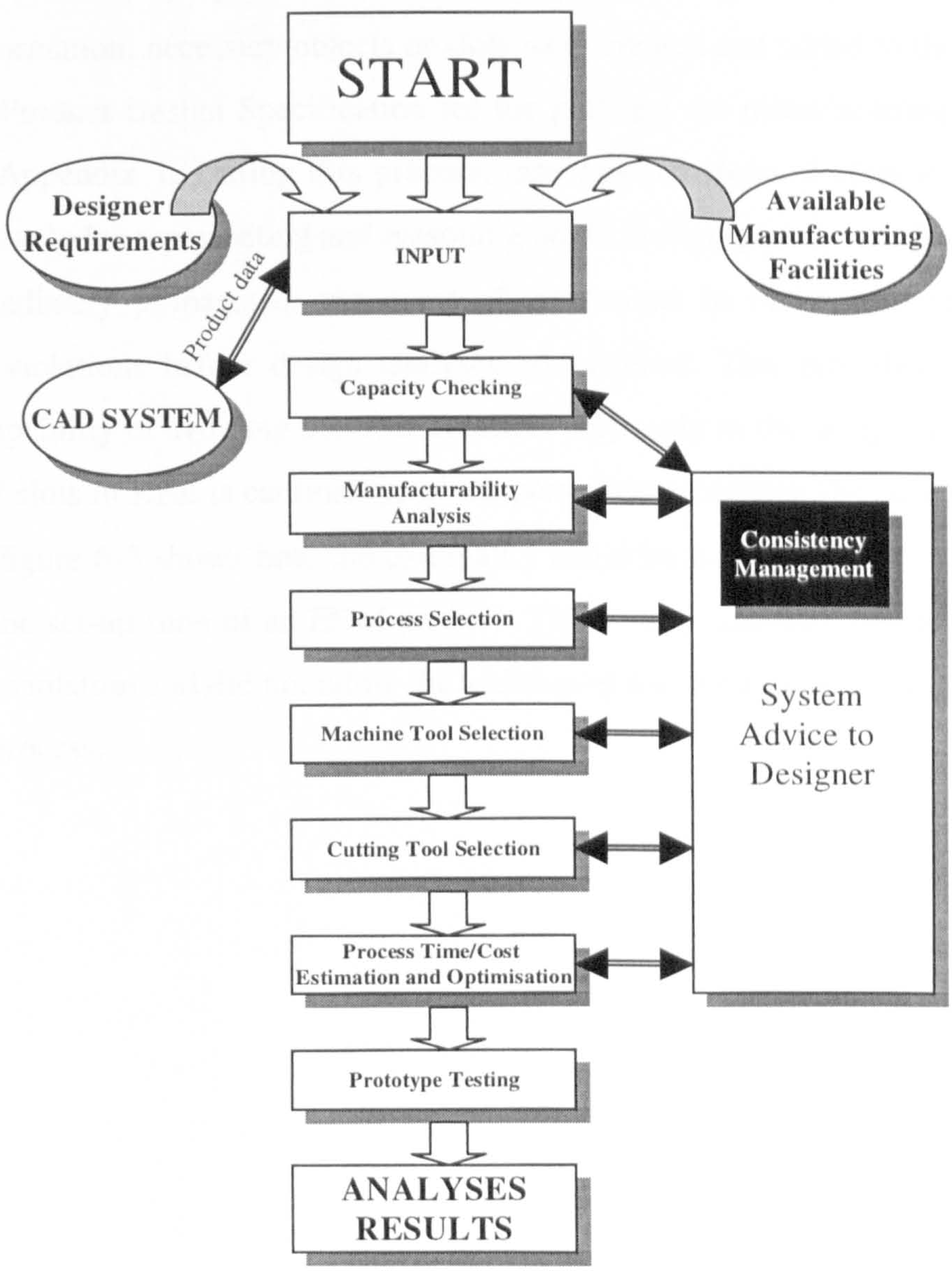
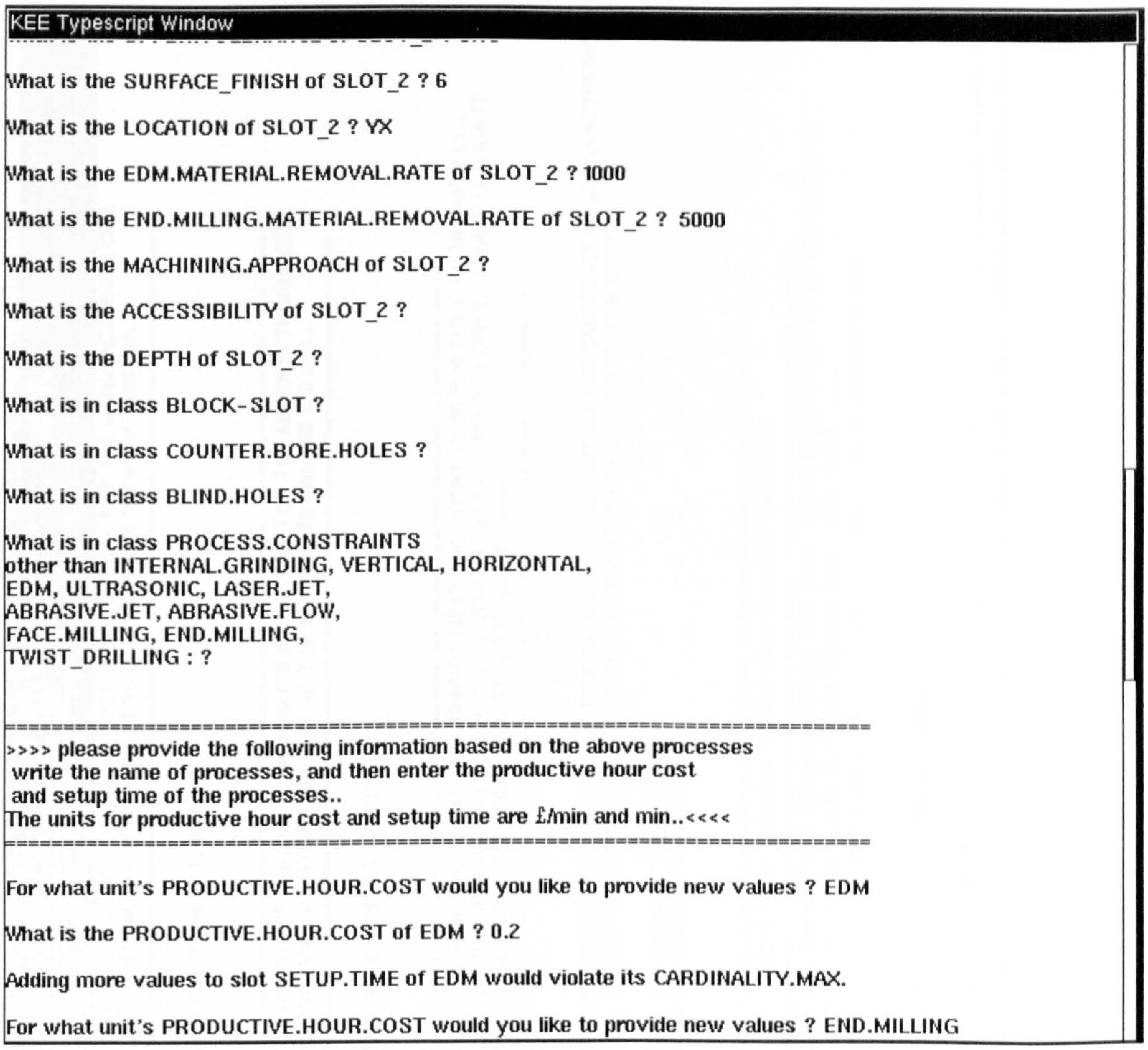


Figure 6-2 The Flowchart for the Various Steps Involved in the Analyses Process

6.4.2 Product Design Specification and Available Manufacturing Facilities

The product design specification (PDS) and the available manufacturing facilities had to be set out before the user started the design analyses process. The PDS included the selected material and its specifications together with the design model with its geometrical and topological attributes and user requirements (maximum process cost and time) in terms of constraints. The available manufacturing facilities contained shape capabilities, production capacity, processes, machines and cutting tools. The system required that this information be provided by the user via the user interface, in order to accomplish the required analyses (Figure 6-3). In this case study, the required information, that was prepared, was automatically stored in the database. Subject to the type of information, necessary objects or slots were created and added to the knowledge base. The Product Design Specification for the part and the manufacturing facilities is shown in Appendix 1. During this process, intervals (attribute of slots in KEE) were used effectively for representing and reasoning on the design parameters. Interval values were immediately propagated, via a set of constraints in order to detect potential constraint violations before design analyses commenced. This provided the designer with the capability of avoiding possible conflicts very early in the design stage. Another attribute of slots in KEE is cardinality, which permitted specifying the number of values of a slot. Figure 6-3 shows how the cardinality could be used to restrict the number of values of the set-up time of an EDM process. The system informed the designer of the cardinality violation and did not allow the addition of a second value to the slot set-up in the EDM process.



```
KEE Typescript Window

What is the SURFACE_FINISH of SLOT_2 ? 6

What is the LOCATION of SLOT_2 ? YX

What is the EDM.MATERIAL.REMOVAL.RATE of SLOT_2 ? 1000

What is the END.MILLING.MATERIAL.REMOVAL.RATE of SLOT_2 ?  5000

What is the MACHINING.APPROACH of SLOT_2 ?

What is the ACCESSIBILITY of SLOT_2 ?

What is the DEPTH of SLOT_2 ?

What is in class BLOCK-SLOT ?

What is in class COUNTER.BORE.HOLES ?

What is in class BLIND.HOLES ?

What is in class PROCESS.CONSTRAINTS
other than INTERNAL.GRINDING, VERTICAL, HORIZONTAL,
EDM, ULTRASONIC, LASER.JET,
ABRASIVE.JET, ABRASIVE.FLOW,
FACE.MILLING, END.MILLING,
TWIST_DRILLING : ?

==========================================================================
>>>> please provide the following information based on the above processes
 write the name of processes, and then enter the productive hour cost
 and setup time of the processes..
The units for productive hour cost and setup time are £/min and min..<<<<
==========================================================================

For what unit's PRODUCTIVE.HOUR.COST would you like to provide new values ? EDM

What is the PRODUCTIVE.HOUR.COST of EDM ? 0.2

Adding more values to slot SETUP.TIME of EDM would violate its CARDINALITY.MAX.

For what unit's PRODUCTIVE.HOUR.COST would you like to provide new values ? END.MILLING
```

Figure 6-3 Product Design Specification of the Various Requirements of the Product's Life Cycle

6.4.3 Manufacturing Capacity Checking

Manufacturing capacity checking was the first step in commencing the design analyses. The information obtained from the user, via the user interface, was used to carry out this analysis. At this stage, in the system, the manufacturing capacity agent checked the available manufacturing capacity against the user requirements and the specification of the design model. As the manufacturing capacity was defined to be between 100 and 1000 per shift, and the user requirement was 99 per shift, there was an inconsistency between these two requirements. Warnings were given to the user, on the design consistency control panel, via active images as shown in Figure 6-4.

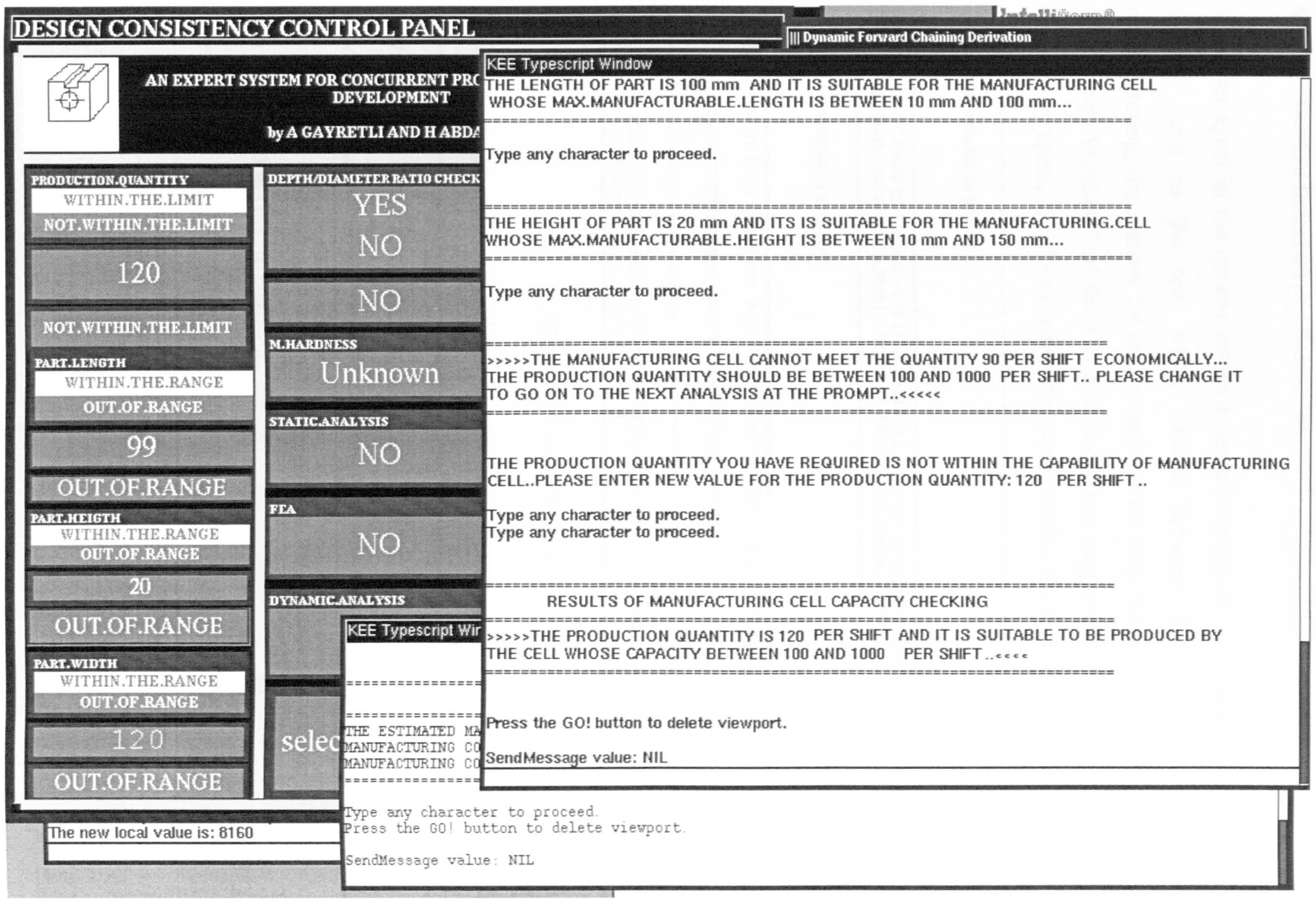


Figure 6-4 The Design Consistency Control Panel Shows Inconsistencies

6.4.3.1 Conflict Detection and Resolution

When an agent in the system detected inconsistencies or when any constraints were violated such as the one, which existed between the user requirement and manufacturing, the reasons for the inconsistencies were immediately generated in the "Typescript Windows" of the user interface. Then suggestions were generated, by the consistency agent, in order to enable the user to resolve the conflict (Figure 6-5).

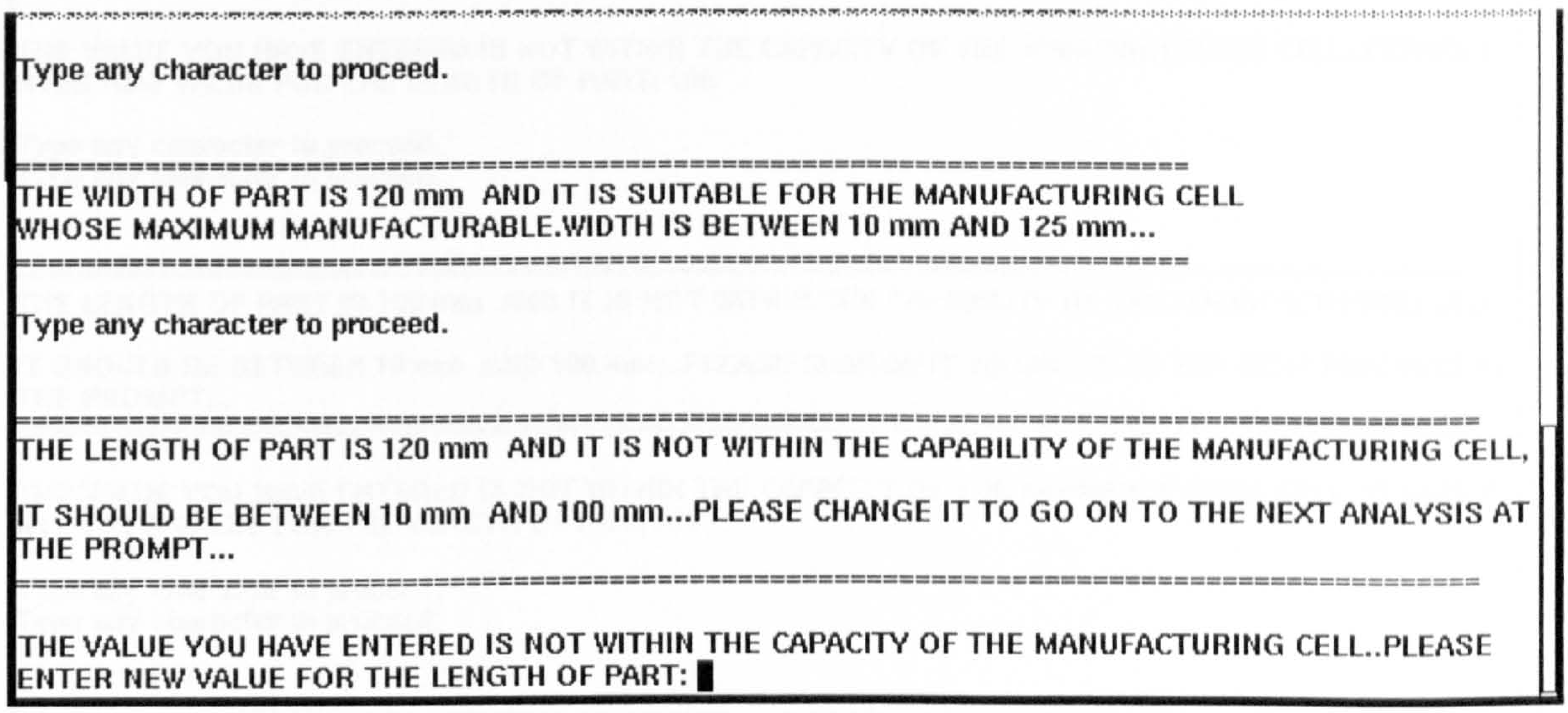


Figure 6-5 Conflict Resolution

Then, the programme stopped running for a while and waited for information to be typed by the user at the prompt window. The new information was propagated again. If neither violations in the design consistency panel nor warnings were reported by the system, the manufacturing capacity checking was complete. Finally, the results of the manufacturing capacity checking are displayed in the "Typescript Windows" for the user's information (Figure 6-6).

```
KEE Typescript Window
=========================================================================
THE WIDTH OF PART IS 120 mm  AND IT IS SUITABLE FOR THE MANUFACTURING CELL
WHOSE MAXIMUM MANUFACTURABLE.WIDTH IS BETWEEN 10 mm AND 125 mm...
=========================================================================

Type any character to proceed.

==========================================================================================
THE LENGTH OF PART IS 120 mm  AND IT IS NOT WITHIN THE CAPABILITY OF THE MANUFACTURING CELL,

IT SHOULD BE BETWEEN 10 mm  AND 100 mm...PLEASE CHANGE IT TO GO ON TO THE NEXT ANALYSIS AT
THE PROMPT...
==========================================================================================

THE VALUE YOU HAVE ENTERED IS NOT WITHIN THE CAPACITY OF THE MANUFACTURING CELL..PLEASE E
NTER NEW VALUE FOR THE LENGTH OF PART: 100

Type any character to proceed.
Type any character to proceed.

==========================================================================================
THE LENGTH OF PART IS 100 mm  AND IT IS NOT WITHIN THE CAPABILITY OF THE MANUFACTURING CELL,

IT SHOULD BE BETWEEN 10 mm  AND 100 mm...PLEASE CHANGE IT TO GO ON TO THE NEXT ANALYSIS AT
THE PROMPT...
==========================================================================================

THE VALUE YOU HAVE ENTERED IS NOT WITHIN THE CAPACITY OF THE MANUFACTURING CELL..PLEASE E
NTER NEW VALUE FOR THE LENGTH OF PART: 99

Type any character to proceed.
Type any character to proceed.

=========================================================================
THE LENGTH OF PART IS 99 mm  AND IT IS SUITABLE FOR THE MANUFACTURING CELL
 WHOSE MAX.MANUFACTURABLE.LENGTH IS BETWEEN 10 mm AND 100 mm...
=========================================================================
```

Figure 6-6 Results of Manufacturing Capacity Checking

6.4.4 Manufacturability Analysis

When the manufacturing capacity checking was completed, the manufacturability analysis could be carried out. The manufacturability agent checked the type of part (rotational or non-rotational), the dimensions, depth/diameter ratio (l/d), and accessibility of the manufacturing form features. In the case study, the diameter of the holes was restricted to the limit between 8 and 80 mm. In addition, depth/diameter ratio (l/d) was limited up to 8, and type of the part was classified as non-rotational. If any of these constraints were violated, the user was warned immediately. The user was then provided with suggestions on how to solve these conflicts. The system provided the user with a report of any changes that were made on the features via the "Typescript Windows" (Figure 6-6 and Figure 6-7).

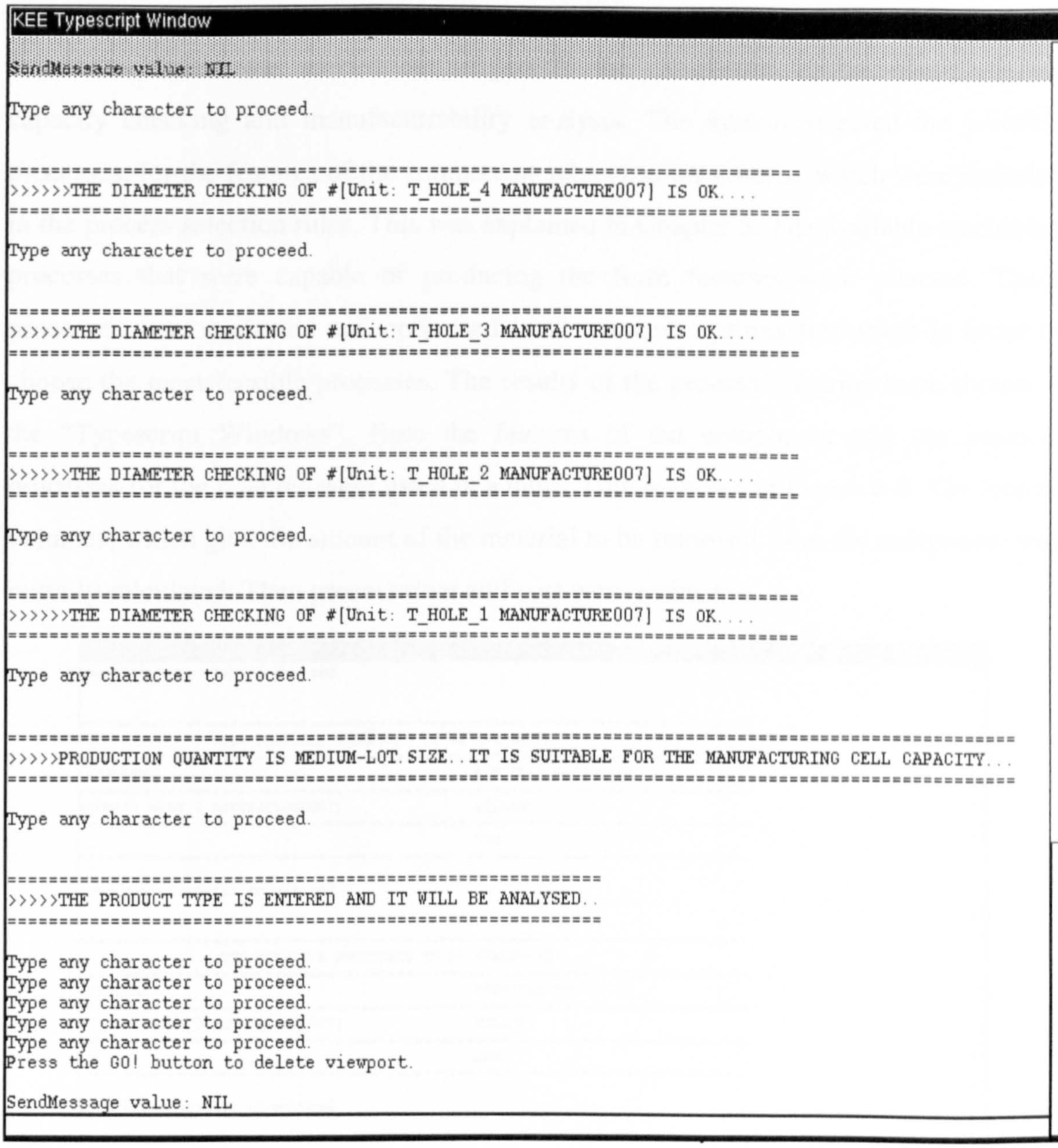


Figure 6-7 Manufacturability Analysis

The new value entered by the user was propagated through the constraint-network to ensure that no constraints, of the design domains, were violated in the system. The manufacturability analysis was completed when no constraint violations were reported by the consistency agent.

6.4.5 Process Selection

Process selection was carried out subject to the completion of the manufacturing capacity checking and manufacturability analysis. The system selected the possible processes, for the features of the component subject to the criteria, which were included in the process selection rules. This was explained in Chapter 5. The available machining processes that were capable of producing the form features were selected. These processes were evaluated and optimised in the process optimisation stage in order to choose the most feasible processes. The results of the process selection were shown in the "Typescript Windows". Here the features of the component and the possible processes for the features were listed in a table. This is shown in Figure 6-8. The feature volumes, which give the amount of the material to be removed from the component was initially calculated. Then process time and cost were estimated.

```
KEE Typescript Window
Type any character to proceed.

=============================================================================
                THE POSSIBLE PROCESSES TO BE EVALUATED
=============================================================================
 FEATURES                                      POSSIBLE PROCESSES
=============================================================================
#[Unit: SLOT_1 MANUFACTURE007]                 MILLING
=============================================================================
                                               EDM
=============================================================================

Type any character to proceed.

=============================================================================
                THE POSSIBLE PROCESSES TO BE EVALUATED
=============================================================================
 FEATURES                                      POSSIBLE PROCESSES
=============================================================================
#[Unit: SLOT_2 MANUFACTURE007]                 MILLING
=============================================================================
                                               EDM
=============================================================================

Type any character to proceed.

==============================================================================
                       THE POSSIBLE PROCESSES TO BE EVALUATED
==============================================================================
 FEATURE                                       POSSIBLE PROCESSES
==============================================================================
#[Unit: T_HOLE_1 MANUFACTURE007]                 DRILLING
==============================================================================
                                               EDM
==============================================================================
                                               MILLING
==============================================================================

Type any character to proceed.

==============================================================================
                       THE POSSIBLE PROCESSES TO BE EVALUATED
==============================================================================
 FEATURE                                       POSSIBLE PROCESSES
==============================================================================
#[Unit: T_HOLE_2 MANUFACTURE007]                 DRILLING
==============================================================================
                                               EDM
==============================================================================
                                               MILLING
```

Figure 6-8 Process Selection

6.4.6 *Cutting Tool Selection*

When the process selection for the form features of the part was complete, the cutting tools to produce the form features were selected. In this case study, the user provided information on the available cutting tools as mentioned in section 6.2.1. Given the selected material with its hardness, the type and dimensions of the form features and the selected feasible process for the component features, the cutting tool selection agent carried out the selection of the cutting tools and displayed the full-results from the cutting tool selection process. This is shown in Figure 6-9.

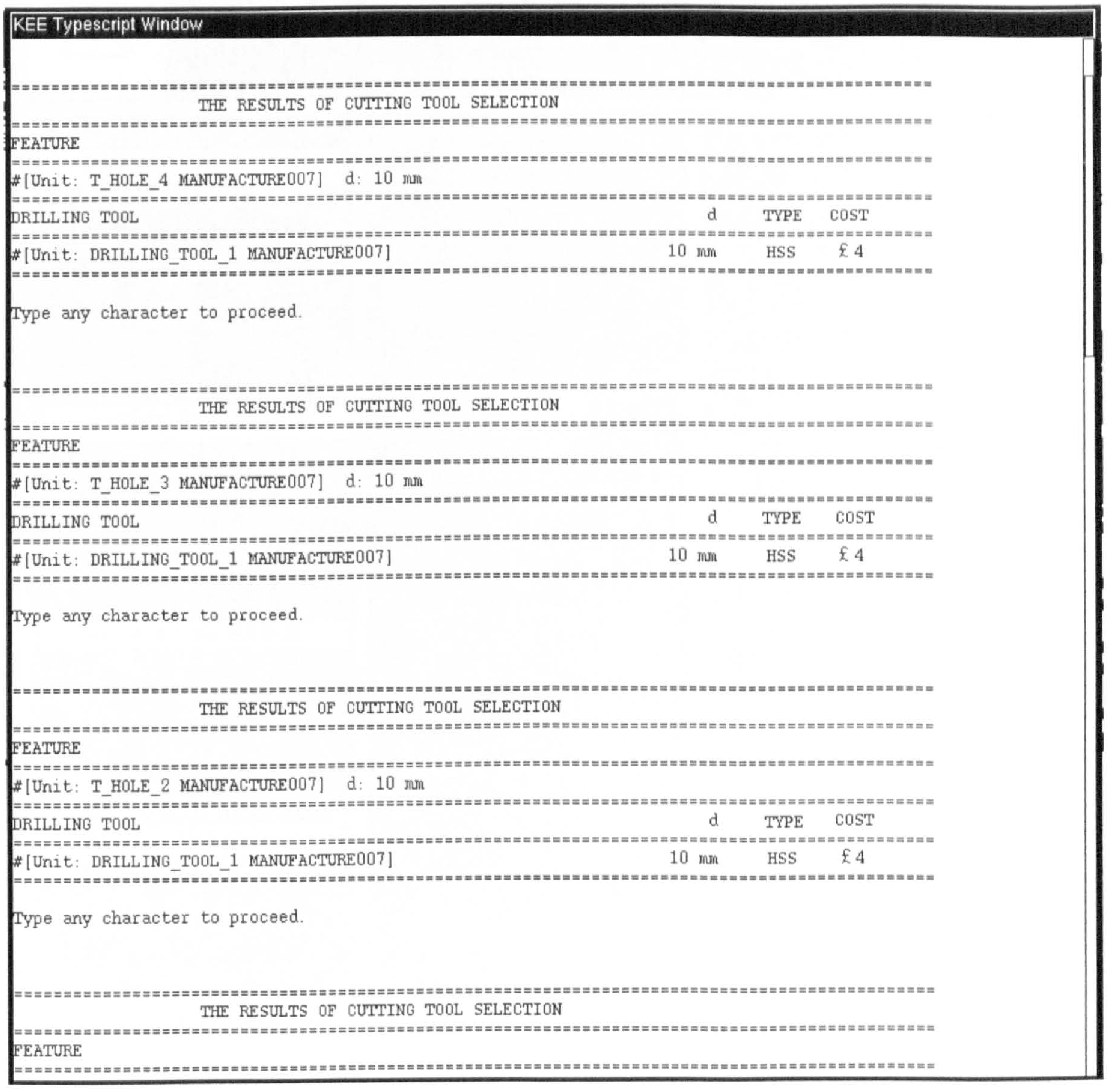


Figure 6-9 Cutting Tool Selection

6.4.7 Machine Tool Selection

The machine tools were chosen depending on their availability and then the cutting tool selection was made. In this case study, it was assumed that a machining centre was available. The machining centre included could accomplish various processes such as drilling, milling, tapping and threading. The available machine tool, which was selected, was displayed in the user interface (Figure 6-10).

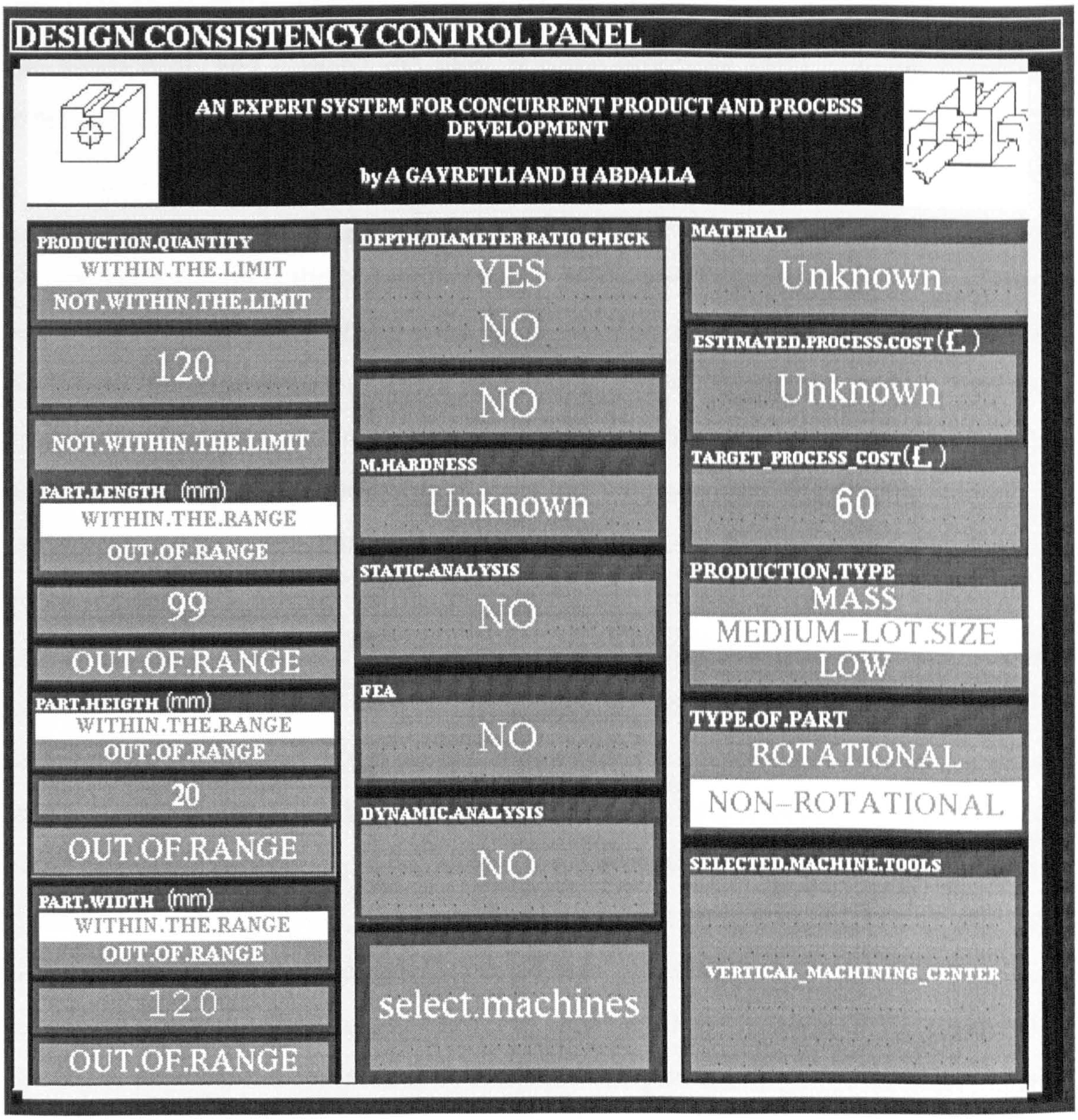


Figure 6-10 A Diagram Shows the Available Machine Tools

6.4.8 Process Time/Cost Estimation and Optimisation

Process time/cost estimation and optimisation is one the most important elements of the design analysis. It gives the designers an idea of the estimated process time and cost of the component. This enables the designer to determine whether or not the designed component can satisfy the pre-defined requirements. The optimisation of the processes for the part was also carried out together with the process time/cost estimation. The process selection and optimisation agent calculated process time/cost of the features of the component, and selected the most feasible processes subject to the pre-defined criteria.

6.4.8.1 Process Optimisation

Design optimisation is the key to concurrent product and process design. It was carried out at all levels of the design process. In this section, how the developed system could deal with the optimisation of the machining processes for the part's features is explained. The optimisation process included various steps (Figure 6-11). When the designer chose process optimisation from the "Concurrent Engineering Menu" the optimisation agent immediately started to analyse form features, select possible processes for each feature and the criteria for the optimisation and evaluation of the processes. To do this a table was generated by the agent (Table 6-1). The table contained constraints for processes of each feature, subject to their input about process time, cost and tool cost. Agent carried out process time and cost calculations for possible processes of the form features. Each form feature was matched with a number of processes that could be used to produce it. For T_Hole_1 there were three possible processes, Drilling, EDM and Milling. For Slot_1 there were two possible processes, EDM and Milling as shown in Figure 6-8. The generation of this table helped to determine possible processes, for each form feature in order to carry out the evaluation of the combination of all processes for the component by assigning one process only to each feature in turn. This helped the designer to evaluate hundreds of process combinations for the part. However, this process may take a lot of time to find available and feasible processes for each feature. Therefore, in order to find feasible processes in reasonable amount of time, the processes, which were not feasible, had to be omitted from the table. The rule-based algorithm was developed to deal with this problem.

The system also provided the designer with the ability of defining maximum process cost and time for the part. This provided the system with flexibility to keep total process cost and time of the part to the predefined values. Then, the system evaluated the possible processes, for machining the form features of the part, by comparing process costs and times, and the other variables against the user requirements. Feasible processes were considered to be the ones satisfying the user requirements. It was possible to select one of the feasible process combinations as a solution or further evaluation was possible. The predefined constraints could be changed to obtain a feasible solution to satisfy the given requirements. Maximum process time and cost could be re-defined by the designer to obtain a feasible set of process combination if necessary. The results of the process selection and optimisation was shown in Figure 6-12.

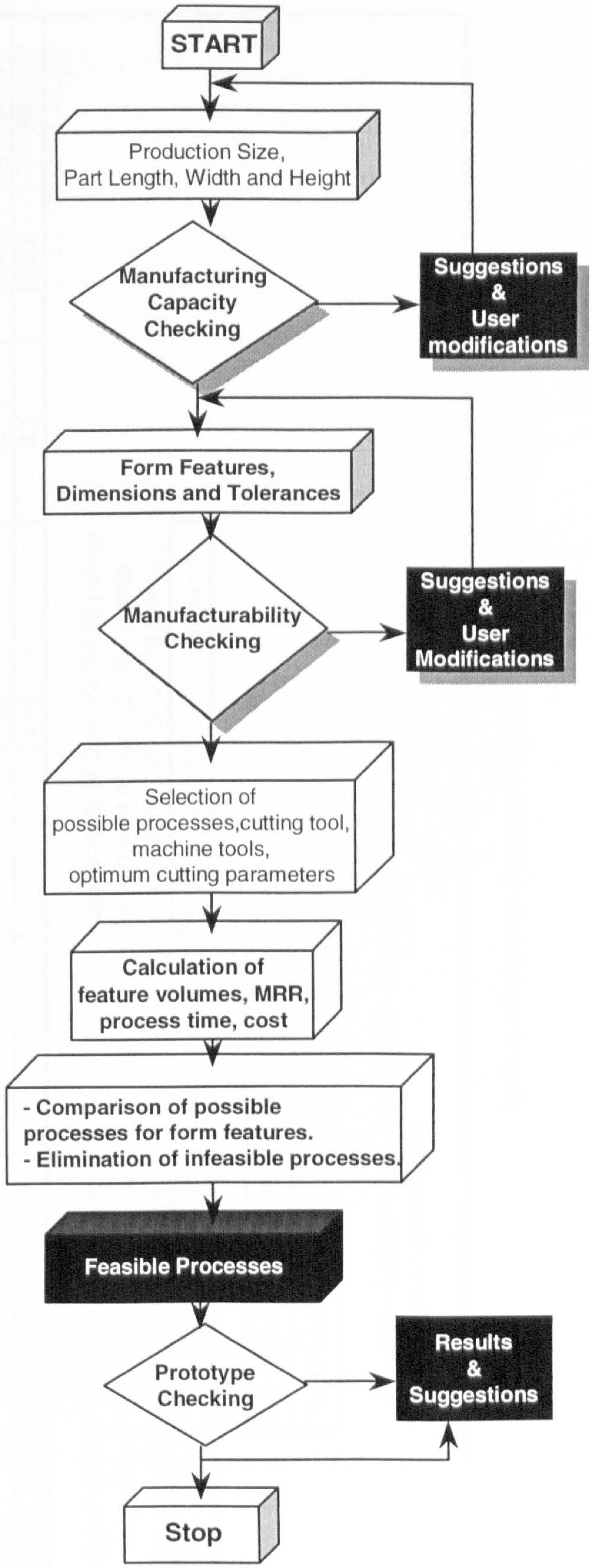


Figure 6-11 Steps in Process Optimisation

Part Name: Cylinder Head, Quantity: 100							
Features	Processes	Machining Time (min)	Set-up Time (min)	Machining Cost (Labour Cost) (£)	Set-up Cost (£)	Tool Cost (£)	Total Cost* (£)
T_Hole_2	EDM	0.8	30	32.4	12.15	32.4	76.95
	Drilling	0.23	20	9.24	8.1	9.24	26.58
	Milling	0.16	20	6.48	8.1	6.48	21.06
Slot_2	EDM	3.12	30	126.36	12.15	126.36	264.87
	Milling	0.16	20	25.28	8.1	25.28	58.66

Labour cost of T_Hole_2= 6.48 pence
Set-up cost of T_Hole_2= 8.1 pence
Tool cost of T_Hole_2= 6.48 pence
Total cost of T_Hole_2= 21.06 pence

Labour cost of Slot_2= 25.28 pence
Set-up cost of Slot_2= 8.1 pence
Tool cost of Slot_2= 25.28 pence
Total cost of Slot_2= 58.66 pence

The total cost of the lot ~ £ 80

The total cost of one piece~ 80 pence

Total cost = Labour cost+ Set-up cost+ Tool cost

* Material cost not included.

Table 6-1 Processes- Features Table for Process Optimisation

```
KEE Typescript Window
                    THE RESULTS OF PROCESSES EVALUATION AND COST-TIME FIGURES
==========================================================================================
 FEATURE                                         TIME(min/unit)        TOTAL COST(£) / 100 unit
==========================================================================================
 #[Unit: T_HOLE_2 MANUFACTURE007]
==========================================================================================
 MACHINING PROCESSES        DRILLING             0.23                       26.85
==========================================================================================
                            EDM                  0.80                       76.95
==========================================================================================
                            MILLING              0.16                       21.06
==========================================================================================

Type any character to proceed.
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>>>>> THE FEASIBLE PROCESS OF #[Unit: T_HOLE_2 MANUFACTURE007]  IS   MILLING   AND
 ITS COST IS £21.06 ..


Type any character to proceed.
Type any character to proceed.
Type any character to proceed.


==========================================================================================
                 THE RESULTS OF PROCESSES EVALUATION AND COST-TIME FIGURES
==========================================================================================
 FEATURE                                     TIME (min/unit)       COST(£) / 100 unit
==========================================================================================
   #[Unit: SLOT_2 MANUFACTURE007]
==========================================================================================
 MACHINING PROCESS                EDM          3.12                 264.87
==========================================================================================
                                 MILLING       0.16                  58.66
==========================================================================================

Type any character to proceed.
Type any character to proceed.


>>>>> THE FEASIBLE PROCESS OF #[Unit: SLOT_2 MANUFACTURE007]  IS END.MILLING AND
 ITS COST IS £58.66 ..


Type any character to proceed.
Type any character to proceed.
Type any character to proceed.

==========================================================================================
                 THE RESULTS OF PROCESSES EVALUATION AND COST-TIME FIGURES
```

Figure 6-12 Process Time/Cost Calculation and Optimisation

In the case of a hole with an aspect ratio (l/d) which is greater than 20, the system selected a non-traditional machining techniques which is EDM. Despite the cost of this process is much higher than the other processes, it is the only feasible process to machine this particular feature as shown in Figure 6-13. In the case of generating the air cooling holes in a gas turbine blade, the aspect ratio of a hole is bigger than 20.

```
KEE Typescript Window
                    THE RESULTS OF PROCESSES EVALUATION AND COST-TIME FIGURES
==========================================================================================
FEATURE                                             TIME(min/unit)      TOTAL COST(£) / 100 unit
==========================================================================================
#[Unit: T_HOLE_2 MANUFACTURE007]
==========================================================================================
MACHINING PROCESSES      EDM                            8.00                    769.50
==========================================================================================

==========================================================================================

==========================================================================================

Type any character to proceed.
Type any character to proceed.


>>>>> THE FEASIBLE PROCESS OF #[Unit: T_HOLE_2 MANUFACTURE007]  IS   EDM   AND
 ITS COST IS £ 769.50..

Type any character to proceed.
Type any character to proceed.
Type any character to proceed.

==========================================================================================
```

Figure 6-13 Feasible Process Selection for An Air Cooling Holes

6.4.9 Prototype Testing

The prototype testing was carried out by the system after the process time and cost estimations and the selection and optimisation of the feasible processes of the component had been completed. The prototype agent calculated the process cost of all the features of the part, and compared it to the predefined process cost in the PDS. The results of this comparison were displayed in the Typescript Window and the design consistency control panel. Using the results of the prototype testing, the final decision on manufacturing the component could be made (Figure 6-14).

```
Type any character to proceed.

======================================================================
                            PROTOTYPE TESTING
======================================================================
THE ESTIMATED MANUFACTURING COST OF PART IS LOWER THAN THE PROPOSED TARGET
MANUFACTURING COST..THE TARGET MANUFACTURING COST IS £60 AND THE ESTIMATED
MANUFACTURING COST £50.
======================================================================

Type any character to proceed.
Press the GO! button to delete viewport.

SendMessage value: NIL
```

Figure 6-14 Prototype Testing

6.4.10 Agents Communication

Communication is one of the most important issues in an agent-based environment. There were interdependencies between design activities represented by the agents in the system. This required interactions and information sharing between these agents in order to carry out design analyses. To provide efficient information processing, amongst agents in order to achieve their individual goals without any conflicts, the agents shared an object-oriented knowledge base, which was easily accessible to each agent. Design analyses were sequentially carried out by the agents. However, the consistency agent was active during the analyses, in order to efficiently deal with constraints violation. It provided the designer with the capability to detect, display and resolve conflicts and worked co-operatively with other agent in order to manage interdependencies between design tasks performed, so as to achieve a successful design that satisfied all the constraints.

6.4.11 Consistency Monitoring

Consistency monitoring was another advantages of the developed system. It enabled the designer to monitor inconsistencies during the design analyses. This helped designers to understand what was really happening during the decision-making. The system provided the designers with consistency monitoring, via the design consistency panel and in the Typescript Window, which were parts of the user interface. The panel consisted of a number of active images linked to the slots, which included the value of a design variable (in this case, it was the production size), which had to be monitored.

When the conflict between the maximum manufacturing capacity and the predefined component's length as explained in section 6.2.2.1, was resolved, this would be shown in the design consistency panel (Figure 6-15). The "Typescript Windows" enabled the designers to monitor the inconsistencies. It provided them with reasons in the form of text. The system also offered the designers with the ability to solve the inconsistencies through the consistency agent during the analyses. The consistency agent provided the designers with the suggestions as shown in Figure 6-6. Any changes made were immediately highlighted on the consistency panel. No violations would be monitored if all the constraints were satisfied.

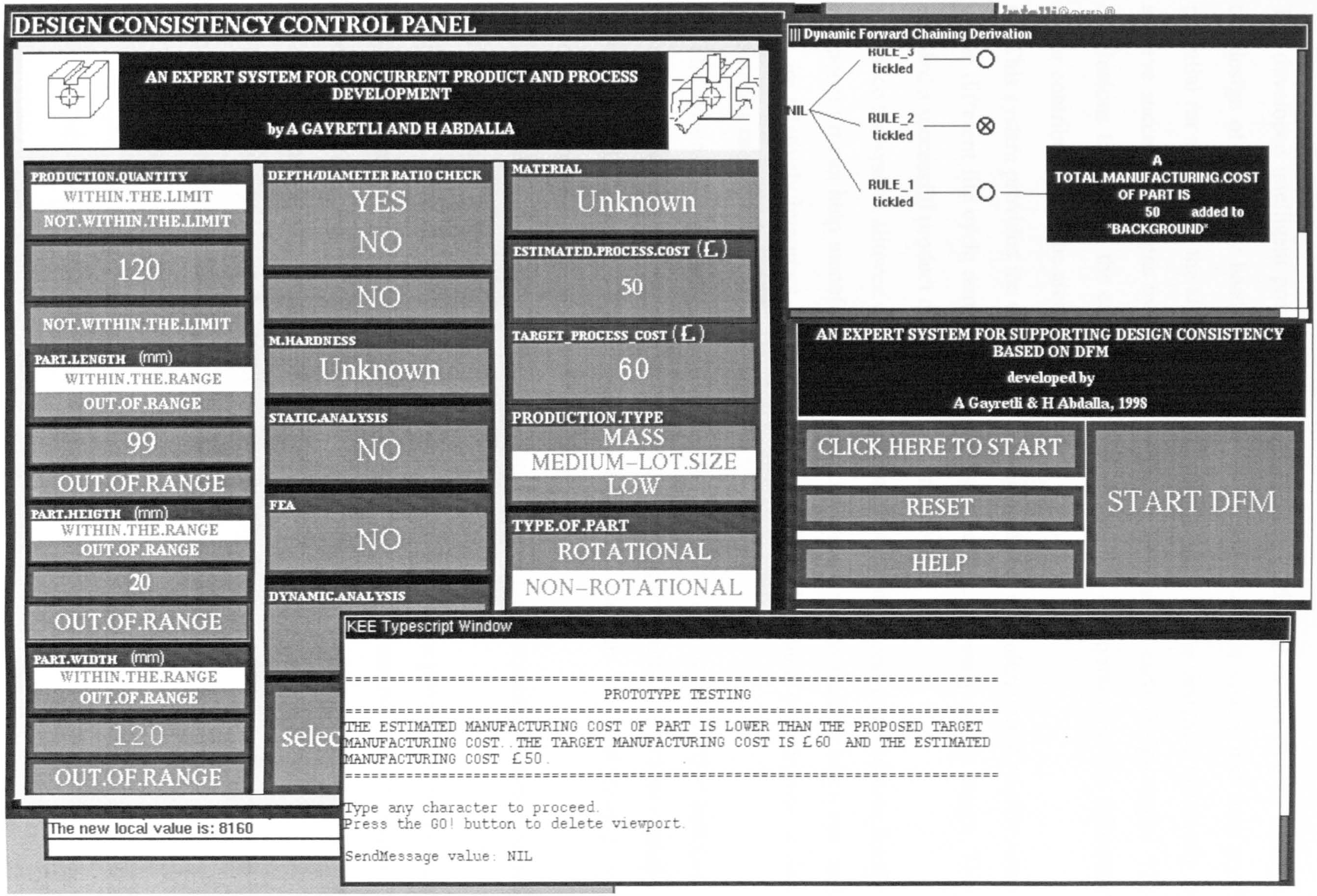

Figure 6-15 Consistency Monitoring

6.5 Conclusion

The developed intelligent prototype system has been evaluated in this chapter through the design of a cylinder head. The case study showed that this system had very good potential for supporting the aims of CE and could be used by the designers efficiently to achieve successful designs by avoiding design conflicts in the early design stages. The conclusions taken from the case study demonstrated that the system had the following major contributions to the area of CE:

- This system provided the designer with the concurrent consideration of requirements of the different life cycle domains of the cylinder head in the early design stages. This enabled a successful product design to be accomplished.
- Since the system allowed designers to define maximum process cost and time for the component it can help manufacturers to make strategic decision-making when cost and time are relatively important. Also, manufacturers can define their own criteria subject to priorities such as time, cost and tolerance.
- The system enabled designers to design the component in an interactive and user-friendly environment and to optimise it based on user requirements, production capacity, manufacturability analysis, feasible process selection, machine tool and cutting tool selection, optimum cutting parameter selection.
- It provided the optimum utilisation of the available manufacturing facilities, which would lead to cost reduction.
- In order to make the final decision quickly, the designer was provided with the full-results of the analyses of manufacturing capacity checking, manufacturability analysis, material selection, process selection, cutting tool selection, machine selection, process cost/time estimation and optimisation.
- The consistency management system provided the designer with the ability to detect, monitor and resolve conflicts, which arose from different design areas.
- The system provided the designer with explanations for the reason for the conflicts, and displayed alternatives from which the user had to make selection to solve the conflict. This ensured that the design was consistent with the product's life cycle requirements.

Overall, it can be concluded that the following was possible:

1) ***Avoidance of design conflicts, which lead to costly-design iterations through an effective consistency management system,***
2) ***Providing the designer with results of various design analyses such as process selection and optimisation and prototype testing to make final decisions on design quickly,***
3) ***Enabling the maximum and economical use of the available manufacturing facilities to lower product cost via the feasible process selection and optimisation.***
4) ***Since the developed system enables companies to define their own criteria such as time, cost and quality the use of the system can help them to make strategic decision-making on launching new products.***
5) ***Optimisation of the design subject pre-defined criteria and various design tasks such as production capacity and manufacturability analysis.***

CHAPTER 7

7 OVERALL CONCLUSIONS

The research work described in this thesis has three major contributions to implementing the concurrent engineering philosophy: integration, optimisation and design consistency. It was carried out to integrate various issues in a product's life cycle, in a more consistent manner and in the early stages of the design process, in order to enable designers to achieve successful product designs that satisfied all the requirements that arise from these life cycle issues. This provided the designers with the ability to optimise product designs subject to the predefined criteria by avoiding any conflicts in the design process. This was achieved only by the use of state-of-the-art IT tools in an integrated environment.

The literature survey in Chapter 2 indicated that current models could not offer a complete solution to the integrated product development. This was because of limitations on the consideration of requirements of various life cycle domains, which had to be met by the designed product. This necessitated complex and timely interactions between various areas. For these reasons, a new integrated study of the concurrent engineering methodology for designing mechanical components has been demonstrated in this thesis. A prototype constraint-based design environment has been developed for achieving such an integration leading to the successful implementation of the concurrent design methodology in the design process.

The achievements of this research work are as follows:

1. A constraint-based design environment for concurrent design of components was developed by incorporating various life cycle requirements into the design process.
2. The integration of important aspects of the design process such as capacity checking, process selection, optimisation and prototype testing were achieved.
3. The process selection and optimisation of the intended components in terms of user requirements and process time were achieved.

4. Achievement of a higher level of consistency between the above design aspects through a conflict resolution system.

5. The system enabled designers to design components in an interactive and user-friendly environment and to optimise it based on pre-defined requirements, production capacity, manufacturability analysis, feasible process selection, machine tool and cutting tool selection, optimum cutting parameter selection.

6. The developed system enabled companies to define their own criteria such as time, cost and quality, hence helping them to make strategic decision-making on launching new products.

7. Complete results of all design analyses in the early stages of the design process.

The major findings of this research work are summarised as follows.

7.1 An Intelligent Design Environment for Concurrent Product and Process Design

A prototype system for Concurrent product and process design has been developed. This system enabled designers to achieve successful product designs by concurrent consideration of all downstream issues related to the product life cycle in the early design stages through the constraint-based system. The developed system dealt with design conflicts between different life cycle domains. It also provided process selection, time/cost estimation and optimisation in order to help designers to determine the feasibility of the intended component in the early stages of the design process. The research described in this thesis represents major contributions to the area of concurrent engineering. These can be summarised in the following sections:

7.1.1 Integration of The Life Cycle Issues Through The Constraint-Based System

As concurrent engineering philosophy aims to incorporate all issues associated with the product's life cycle into the design phase in the early design stages, the integration of some of these issues such as PDS, material selection, manufacturing capability and process selection has been demonstrated in Chapter 3. Information from different design areas was organised in the form of objects and constraints in order to carry out various design analyses. The developed system contained the following features:

1. The integration of various issues in a product's life cycle- part representation, product design specification, manufacturability analysis, process selection and optimisation, manufacturing capacity checking, process cost/time estimation, machine and cutting tool selection and prototype testing. The system enabled designers to have a complete result of these tasks during the design process (Chapter 3 and 4).

2. The system included the requirements of the life cycle issues of the product, in the form of objects and constraints. This provided an easy and effective organisation of design and manufacturing knowledge.
3. The integration of production rules with object-oriented programming was achieved in the same rules classes to reduce the number of rules, create more powerful rule application and make the system flexible, and run more efficiently.

4. A user-friendly interface consisted of menus for design analyses, a design consistency panel for monitoring inconsistencies and a "Typescript Window" for providing the designer with complete results of the analyses and conflict resolution.

5. This system could be extended easily to achieve the involvement of other activities of product's life cycle into the design process.

7.1.2 Process Selection, Time/Cost Estimation and Optimisation

Since process selection, cost estimation and optimisation are important issues in product design, a methodology for the evaluation and optimisation of manufacturing processes was developed. The major contributions of this methodology are summarised as follows.

1. It provided designers with the ability to design products concurrently, select manufacturing processes and evaluate and optimise them by the consideration of different product life cycle requirements and user constraints and avoiding design conflicts.

2. The methodology enabled designers to carry out real-time cost estimation, generate feasible process plans, and deal with conflict situations using the constraint-based system.

3. A rule-based algorithm for the estimation and optimisation of manufacturing processes was developed. The rule-based algorithm provided the evaluation of available processes for the features of parts in terms of user requirements and process time/cost (Chapter 5).
4. Designers were provided with a complete report on results of the process selection, time/cost estimation and optimisation, in order to ensure the manufacturability of the intended part.

5. The results drawn from the system were promising. Using this system, a significant reduction in the product cost and lead-time could be achieved.

7.1.3 Design Consistency

In order to carry out the design tasks, by avoiding design conflicts between the different design domains, a design consistency management module was developed and linked to the system. From the design consistency point of view, the major contributions from this research work are summarised as follows.

1. An effective management of information exchange and decision making within agents (design areas) was developed. This was based on the constraints programming technique presented in (Section 4.7.1, pp. 92-94)

2. This system enabled designers to consider various critical tasks (overall co-ordination, control, consistency, and data integrity).

3. Design inconsistencies between different design domains were overcome by a conflict resolution system (Section 4.7.2, pp. 95, Section 4.7.3, pp. 96-97, Section 6.2.9, pp. 134), which in turn reduced product development time.

4. The designers could monitor design inconsistencies through a design consistency panel, which was part of the user interface. It included menus for design analyses and conflict resolution, active images for consistency monitoring and textural displays for the results of the analyses.

7.2 Summary

The developed system enabled designers to concurrently design successful products, in an interactive design environment, with the complete satisfaction of the various types of requirements arising from different aspects of the product's life cycle, by avoiding design inconsistencies that resulted in the design iterations leading to longer lead-time and higher product cost.

This system provided the designer with an interactive design environment where successful concurrent product designs were achieved with a high level of overall consistency by:

- ***Full integration of design and manufacturing activities via the proposed approach,***
- ***Avoiding design inconsistencies, which resulted in costly-design iterations through an effective consistency management system, hence less product development time,***
- ***Providing the designer with the capability of making final decisions on designs quickly via the results of various design analyses such as process selection and optimisation and prototype testing,***
- ***Enabling the manufacturers to produce products with the maximum and economical utilisation of the manufacturing facilities available to reduce product cost via the feasible process selection and optimisation.***
- ***The developed system provided companies with the ability of defining their own criteria such as time, cost and quality, hence helping them to make strategic decision-making on launching new products.***

CHAPTER 8

8 RECOMMENDATIONS

This research work has contributed to the implementation of concurrent engineering strategy from three perspectives: integration, optimisation and design consistency. However, many interesting questions have been raised in this thesis. Further research is required to extend concurrent engineering framework so that the involvement of all issues related to the product's life cycle can be achieved, in order to design components satisfying all the requirements of these issues. A broader framework could be developed through suitable extensions to this research. Future research that is necessary in several areas is summarised as follows.

8.1 Integration

Concurrent engineering is a systematic approach. It aims to incorporate the product's life cycle issues into the design phase, at an early design stage in order to reduce product cost and lead-time. In this research work, the integration of many of these issues has been achieved. However, there are other important domains that need to be involved in the design process, in order to bring the full benefits of the implementation of the concurrent engineering philosophy to the manufacturers. For this reason, the other issues such as assembly, disposability and recyclability need to be integrated to achieve a higher level of concurrency between different design areas.

8.2 Information Modelling and Management

Information related to the different design areas needs to be modelled in a format that can be utilised for executing different design tasks. The techniques used for information modelling in this research work had certain limitations. Firstly, complex designs were not easy to represent in the form of constraints. Secondly, a huge amount of information would be needed in the form of various types of modelling techniques so as to effectively use the information.

However, this may lead to data incompatibility between different design domains. Therefore, it is necessary to implement standard data exchange protocols (STEP). The solution in constraint-based intelligent systems is reached by the satisfaction of all the constraints associated with a problem. The procedure for this is sequential, namely each design task has to be carried out. This can be seen as a boring process. Therefore, the multi-agent approach needs to be fully adapted for the existing system to achieve the efficient management of information exchange and decision-making activities and carry out design tasks concurrently.

8.3 Process Selection and Optimisation

There are many issues related to process selection and optimisation that have to be exploited. These issues should be included in the design process in order to achieve the successful implementation of the concurrent product development. Further research effort is required in areas such as sequencing, tool path analyses and scheduling, in order to achieve the involvement of requirements of these areas in the design process.

8.4 Quantification of Achievable Benefits

Although, a case study has demonstrated that real benefits can be seen in the developed system, it is necessary to test the system on a wider range of industrial products. This could provide the basis for quantification benefits from the use of the system. The case study carried out here has demonstrated that the system provided the designer with the full report on the feasibility of manufacturing the intended component at the early design stages. This would help designers to determine whether the part was economically manufacturable. However, a full cost estimation exercise should be carried out which real costs supplied by industry, in order to quantify possible benefits from the system. Also, in order to reduce process costs the relevance of Group Technology (GT) as a technique for grouping similar parts should be investigated.

8.5 Application

The prototype system developed in this research work could be used as a decision support tool for concurrent product development, which would assist designers and process planners in designing products at lower cost with shorter lead-time and with a higher customer satisfaction. The system has been developed to be a useful concurrent decision support system with due regard to industrial expectations, use and acceptability. However, further testing for different type of complex products in various industrial sectors should be carried out to identify the full benefits and the problems of using the prototype system for possible future improvement. The difficulty in obtaining correct and accurate data from industry was a problem, which does not allow the real potential benefits of the developed system to be realised. Group Technology (GT) could be implemented for classifying similar products in order to lower production cost and shorten process time.

REFERENCES

Abdalla, H S, (1999), " Concurrent Engineering for Global Manufacturing", *Int. J. Production Economics*, 60-61, 251-260.

Abdalla, H., Knight, J.A.G., (1994) " A Featured Based Design Environment for Concurrent Engineering", *The Proceedings of the International Conference on CE and Electronic Design Automation*-(CEEDA'94).

Abdalla, H.S., Knight, J., (1994) "An Expert System for Concurrent Product and Process Design of Mechanical Parts", *Proc. Instn. Mech. Engrs*, Vol. 208, pp. 167-172.

Al-Ashaab, A H and Young, R I M, Unpublished Paper " A Manufacturing Model: Supporting Concurrency in Injection Moulded Product Design" unpublished paper, Dept. of Manu. Eng., LUT, Loughborough, Leicester, UK.

Al-Ashaab, A H and Young, R I M, (1995) " Design for Injection Moulding in a Manufacturing Model Environment", *Journal of Design and Manufacture,* Vol.5, pp. 45-54.

Alting, L., "Life-Cycle Design of Products: A New Opportunity for Manufacturing Enterprises", *Concurrent Engineering: Automation, Tools, and Techniques*, Edited by A Kusiak, John Wiley & Sons, pp.1-17 (1992).

Anumba, C J and Evbuomwan, N F O, (1999), " A Taxonomy for Communication Facets in Concurrent Life-Cycle Design and Construction", *Microcomputers in Civil Engineering,* Vol. 14, No.1, pp. 37-44(8).

Asiedu, Y and Gu, P (1998) " Product Life Cycle Cost Analysis: State of The Art Review" *International Journal of Production Research*, Vol. 36, No. 4, pp. 883-908.

Korves, B and Loftus, M, (1999) "The application of immersive virtual reality for layout planning of manufacturing cells", Proc Instn Mech Engrs Vol 213 Part B, pp. 87-91.

Balasubramanian, S. and Norrie, D., H., (1996) " A Multi-agent Architecture for Concurrent Design, Process Planning, Routing, and Scheduling", *Concurrent Engineering: Research and Application*, Vol.4, No.1, pp. 7-15.

Berrais, A "Knowledge-based Expert Systems: User Interface Implications" *Advances in Computational Structure Technology*, Civil-Comp Press, Edingburg, pp.185-195, 1996.

Bowen, J, (1997) " Using dependency records to generate design co-ordination advice in a constraint-based approach to concurrent engineering", *Computers in Industry*, Vol. 33, pp.191-199.

Bullinger, H J, Warschat, J, Bopp, R and Worner, K, (1998) " Approaches to Product Life Cycle Cost Estimation in Concurrent Engineering", http://www.rdm.iao.fhg.de/projecte/toproco/PUBLICATIONS/CEEPAPER.html.

Carver, G and Bloom, H, 1991, " Multi-Enterprise Concurrent Engineering Through International Standards", NISTIR 4708, National Institute of Standards and Technology, Gaithersburg, MD.

Champati, S, Lu, W F and Lin, A C, (1996) " Automated Operation Sequencing in Intelligent Process Planning: A Case-Based Reasoning Approach" *Int. J. Adv. Manuf. Technol.*, Vol.12, pp.21-36.

Chang, T C "Expert Process Planning for Manufacturing", Addison-Wesley, US, 1990.

Chang, T C and Wysk, R A "An Introduction to Automated Process Planning System", Prentice-Hall, US, 1985.

Chang-Xue, F and Kusiak, A "Constraint-based Design of Parts", *Computer-Aided Design*, Vol.27, No. 5, pp. 343-352, 1995.

Choi, H S and Park, K H, (1997) " Shop-floor scheduling at shipbuilding yards using the multiple intelligent agent system", *Journal of Intelligent Manufacturing,* Vol. 8, No. 6, pp. 505-515.

Cleetus, K J, 1992, " Definition of Concurrent Engineering", CERC Technical Report Series-CERC-TR-RN-92-003, Concurrent Engineering Research Center, West Virginia University, USA.

Colton, J.S., "An Intelligent Design for Manufacture System", *Concurrent Engineering: Automation, Tools, and Techniques*, John Wiley & Sons, pp. 153-177(1992).

Cross, N, (1994), Engineering Design Methods: Strategy for Product design, John Wiley & Sons.

Crow, K, (1994) "Building Effective Product Development Teams" http://members.aol.com/drmassoc/pdt.html.

Crow, K, (1997) " Target Costing" http://members.aol.com/drmassoc/target.html.

Cutkosky, M.R., Tenenbaum, J.M., " A Methodology and Computational Framework for Concurrent Product and Process Design", *Mech. Machine. Theor. Des. Theeor. Applic. Mech. & Machine Des.*, Vol. 25, No.3 pp.365-381(1990).

D'Ambrosio, J, Darr, T, and Birmingham, W., "Hierarchical Concurrent Engineering in a Multiagent Framework" *Concurrent Engineering: Research and Applications*, Vol.4, No.1, pp. 47-57, 1996.

Das, D, Gupta, S K and Nau, D S "Estimation of set-up time for machined parts: accounting for work-holding constraints using a vise" *The Proceedings of the Computers in Engineering Conference and the Engineering Database Symposium*, pp.619-631, ASME 1995.

Das, D, Gupta, S K and Nau, D S "Reducing set-up cost by automated generation of redesign suggestions" *Computers in Engineering*, Vol.1, pp.159-170, ASME 1994.

Dean, E, B, and Unal, R, "Elements of Designing for Cost", *1992 Aerospace Design Conference*, Irvine CA, AIAA Paper 92-1057, February 3-6, 1992.

Devireddy, C R and Ghosh, K, (1999) " Feature-based modelling and neural network-based CAPP for integrated manufacturing", *Int. J. Computer Integrated Manufacturing*, Vol. 12, No. 1, pp. 61-75.

Dewhurst, P., and Boothroyd, G., (1988) "Early cost estimating in product design" *Journal of Manufacturing Systems*, Vol.7, No.3, pp. 183-191.

Dong, Z., "Design for Automated Manufacturing", *Concurrent Engineering: Automation, Tools, and Techniques*, pp.207-233 (1992).

Downlatshahi, S (1992) "Product Design in a Concurrent Engineering Environment: an Optimisation Approach" *Int. J. Prod. Res.*, Vol. 30, No. 8, pp. 1803-1818.

Downlatshahi, S and Ashok, M S, (1997) " Design Optimisation in Concurrent Engineering: A Team Approach" *Concurrent Engineering: Research and Application, Vol.5, No.5, pp. 145-154.*

Duan. W., Zhou, J., and Lai, K., "FSMT: A Feature Solid-Modelling Tool for Feature-Based design and Manufacture", *Computer-Aided Design*, Vol.25, pp. 29-38 (1993).

Duda, J and Pobozniak, J, (1995) " Expert System for Process Planning" *The Proceedings of the Thirty-first International MATADOR Conference*, UMIST, Manchester, pp.527-533, April-1995.

Duffy, V G and Salvendy, G, (1999), " Relating company performance to staff perceptions: the impact of concurrent engineering on time to market", *International Journal of Production Research,* Vol.37, No.4, pp. 821-834.

Dym, C., L., (1994), Engineering Design: A Synthesis of View, Cambridge University Press.

ElBaradie, M. A., (1996) " Recycling and clean machining", *Journal of Material Processing Technology,* Vol.56, No.1-4, pp. 798-806.

ElBaradie, M. A., (1997) " A fuzzy logic model for machining data selection", *International Journal of Machine Tools & Manufacture,* Vol.37, No.9, pp. 1353-1372.

ElBaradie, M. A., (1997) " Development of a fuzzy logic based expert system for machining data selection", *Proc. Of 14th International Conference on Production Research (14th ICPR),* Osaka, Japan, pp. 1366-1369, August 1997.

Eversheim, W, Roggatz, A, Zimmermann, H-J and Derich, Thomas, (1997) " Information management for Concurrent engineering" *European Journal of Operational Research,* Vol. 100, pp.253-265.

Fen, C J, Kusiak, A and Huang, C "Cost evaluation in design with form features", *Computer-Aided Design*, Vol.28, No.11, pp. 879-885, 1996.

Fu, M C and East, E W, (1999), "The Virtual Design Review", *Microcomputers in Civil Engineering*, vol. 14, no. 1, pp. 25-35(11).

Fu, Z and Nee, A Y C, (1994) “Interpreting Feature Viewpoints for Concurrent Engineering” *Computers in Engineering*, Vol.1, pp.405-411, ASME.

Gadient, A J, Hines, L E, Welsh, J and Schwalb, A P, (1997) “ Agility through Information Sharing: Results Achieved in a Production Setting” *Concurrent Engineering: Research and Applications*, Vol.5, Number.3, pp.101-111.

Gayretli, A and Abdalla, H, (1998a) “ An Expert System for Manufacturing Process Optimisation” *The Proceedings of 2nd International Symposium on Tools and Methods for Concurrent Engineering TMCE’98*, pp. 419-427, Manchester Metropolitan University, April, UK.

Gayretli, A and Abdalla, H, (1998b) " A Feature-Based Prototype System for Evaluation and Optimisation of Manufacturing Processes" *The Proceedings of 24th International Conference on Computers and Industrial Engineering CIE'98*, Brunel University, Middlesex, September, UK.

Gayretli, A and Abdalla, H, (1999) " A Prototype Constraint-Based System for The Automation and Optimisation of Machining Processes", *Journal of Manufacture-Part B,* Vol. 213, pp. 655- 676.

Gayretli, A and Abdalla, H, (1999a) " An Intelligent Design Environment for Concurrent Product and Process Design" *The Proceedings of 15th International Conference on Computer-Aided Production Engineering CAPE'99*, University of Durham, Durham, April-1999, UK, pp. 238-245.

Gayretli, A and Abdalla, H, (1999b) " An Object-Oriented Constraints-Based System for Concurrent Product Development", *International Journal of Robotics and Computer Aided Manufacturing,* Vol. 15, Issue 2, pp. 133-144.

Gayretli, A and Abdalla, H, (1999c) " A Feature-Based Prototype System for Evaluation and Optimisation of Manufacturing Processes" *International Journal of Computers and Industrial Engineering*, Vol. 37, No.1-2, pp. 481-484.

Gayretli, A and Swain, E, (1996) " Design of a Weapon Trolley", *The Proceedings of UMTIK'96 Conference*, METU, September, Ankara-TURKEY.

Gunesekaran, A and Sarhadi, M, (1997)" Editorial-Special Issue on Enterprise Integration and Management Volume No.II: Planning and Management Issues in Enterprise Integration" *Concurrent Engineering: Research and Applications*, Vol.5, No. 2, pp. 98-99.

Gupta, S K, Das, D, Regli, W C, and Nau, D S,"Current Trends and Future Challenges in Automated Manufacturability Analysis" *The Proceedings of the Computers in Engineering Conference and the Engineering Database Symposium*, pp. 655-665, ASME 1995.

Gupta, S K, Nau, D S, Regli, W C, and Zhang, G, " A Methodology for Systematic Generation and Evaluation of Alternative Operation Plans", *Advances in Feature Based Manufacturing*, Elsevier/North Holland, pp.161-184, 1994.

Harrington, J.V., Soltan, H., and Forskitt, M., "Negotiation in a Knowledge-Based Concurrent Engineering Design Environment", *Expert Systems*, Vol. 12, pp. 139-148 (1995).

Hashemian M and Gu P, "A Constraint-based System for Product Design", *Concurrent Engineering: Research and Applications*, Vol.**3**, Number.3, pp.177-185 (1995).

Hashmi, K, ElBaradie, M. A. and Ryan_M, (1998) " Fuzzy logic based intelligent selection for machining parameters", *International Journal of Computers and Industrial Engineering,* Vol.35, No.3-4, pp. 571-574.

Hashmi, K., ElBaradie, M. A. and Ryan, M., (1997) " Fuzzy logic based intelligent selection of machining parameters", *Proc. Of 22nd International Conference on Computers and Industrial Engineering (ICC & IE)*, The American University in Cairo, pp. 309-311, Egypt, December 1997.

Hayes, C C and Su, C S, (1995) "Using a Manufacturing Constraint Network to Identify Cost-critical Areas of Designs" *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, Vol.9, pp. 73-87.

Heisler, H, (1985) " Vehicle and Engine Technology", Edward Arnold, pp. 216.

Horvath, L and Rudas, I, "Fuzzy Supported Object Oriented Petri Nets at Various Levels of Manufacturing Process Planning", *IEEE*, pp. 1428-1433, 1994.

Huthwaite, B., "Manufacturing Competitiveness and Quality by Design", *ICD/FOCUS Method, Proceedings of Fourth International Conference on Product Design for Manufacture and Assembly*, 1989.

Ikonopisov, A., Abdalla, H., Knight, J.A.G.," A Concurrent Engineering Approach to Design for Assembly and Manufacture", Dept. of Mechanical Engineering, De Montfort University, UK (1994).

Institute for Defence Analysis Report R338, 1988.

Ishii, K., "Modeling of Concurrent Engineering Design", *Concurrent Engineering: Automation, Tools, and Techniques*, pp.19-39(1992).

Ismail, M. Y., ElBaradie, M. A. and Hashmi, M. S. J, (1997)" Quality management in the manufacturing industry: Practice vs Performance", *Proc. Of 22nd International*

Conference on Computers and Industrial Engineering (ICC & IE), The American University in Cairo, Egypt, pp. 355-358, December 1997.

Kapur, K C, (1992) "Quality Engineering and Tolerance Design" *Concurrent Engineering: Automation, Tools and Techniques*, John Wiley & Sons, pp. 287-306.

Kim, S H, (1999), "Learning agent architecture for design and manufacturing knowledge on the Web: an extension of enterprise resource planning capabilities", *International Journal of Intelligent Systems in Accounting, Finance & Management*, March 1999, vol. 8, no. 1, pp. 15-24(10)

Kiritris, D, Porchet, M and Belhi, A, (1994) " A Generic Petri Net Model Dynamic Process Planning" *Computers in Engineering*, Vol.1, pp.225-242, ASME.

Kiritsis, D, Porchet, M, and Belhi, A, "A Generic Petri Net Model for Dynamic Process Planning", *Computers in Engineering*, Vol.1, pp.235-242, ASME 1994.

Kotler, P., Marketing Management, Prentice-Hall, pp. 321(1994).

Krishnamurthy, R, McLean, C and Shewchuk, J P, (1998) " A Hybrid Manufacturing System Modeling Environment Using VRLM", NISTIR Reprints, National Institute of Standards and Technology, Gaithersburg, MD.

Krishnaswamy, G M and Elhennawy, A K (1992) "Concurrent Engineering Deployment: An Enhanced Customer Product Approach" *Computers and Industrial Engineering,* Vol. 23, Nos. 1-4, pp. 503-506.

Laakko, T., Mantyla, M., "Feature modelling by Incremental Feature Recognition", *Computer-Aided Design*, Vol. 25, pp.479-492 (1993).

Lander, S E and Corkill, D D, "Designing Integrated Engineering Environments: Blackboard-Based Integration of Design and Analysis Tools" *Concurrent Engineering: Research and Applications*, Vol.4, No.1, pp. 59-70, 1996.

Lee I B H, Lim B S and Nee A Y C, " IKOOPS: An Intelligent Knowledge-Base Object-Oriented Process Planning System for The Manufacture of Progressive Dies", *Expert Systems*, Vol.8, No.1, pp. 19-31 (1991).

Lim, S H, Juster, N and De Pennington, A, (1998), "A role interaction approach to support manufacturing enterprise integration", Proc Instn Mech Engrs Vol 212 Part B, pp. 439-452.

Loeffler and Anderson. *The VR Casebook*, 1994 (Van Nostrand Reinhold, New York).

Luong, L H S and Spedding, T "An integrated system for process planning and cost estimation in hole making" *Int. J. Adv. Manuf. Technol.*, Vol.10, pp.411-415, 1995.

Lyons, K, Angster, S and Jayaram, S, (1997) " Virtual Environments for Design and Manufacture" *Concurrent Engineering-The Agenda for Success*, Chapter 6, Res Studies Press Ltd.

Machining Data Handbook, (1980), Metcut Research Associations Inc., 3rd edition, Vol.1-2.

Marri, H B, Gunasekaran, A, and Grieve, R J, (1998) "Computer Aided Process Planning: A State of Art", *Int. J. Adv. Manuf. Technol.,* Vol.14, pp. 261-268.

Molina, A, Al-Ashaab, A H, Ellis, T I A and Young, R I M, (1995) " A Review of Computer Aided Simultaneous Engineering Systems", *Research in Engineering Design*, Vol. 7, pp. 38-63.

Murgatroyd, I S, Hodgson, A and Weston, R H, (1998), "Enterprise modelling in support of business process visualisation and improvement", *Journal of Engineering Manufacture*, vol. 212, no. 8, pp. 621-633(13).

Noble, J S, "An Approach to Overall Design Consistency in Concurrent Engineering" *International Journal of Flexible Automation and Integrated Manufacturing*, 1(1), pp. 25-36, 1993.

O'Grady, P., Young, R E, Greef, A and Smith, L., "An Advice System for Concurrent Engineering" *Int. J. Computer Integrated Manufacturing*, Vol. 4, No.2, pp. 63-70, 1991.

Oehlmann, R, Thoben, K-D and Weber, F, (1997) " Capturing and assessing formal interaction at task level in product development" *Computers in Industry*, Vol.33, pp.179-189.

Olson, D L and Courtney, J F, *Decision Support Models and Expert Systems*, Maxwell-Macmillan, 1992.

Ostwald, P F, " AM Cost Estimator", Penton Publishing, 4. Edition, US, 1988.

Ou-Yang, C, and Lin, T S, (1997) "Developing an Integrated Framework for Feature-Based Early Manufacturing Cost Estimisation" *Int. J. Adv. Manuf. Technol.*, Vol.13, No.9, pp. 618-629.

Palmer, G J and Hall, D M, (1992) " Minimum Cost Selection and Sequencing of Volume Removal Operations, Using Artificial Intelligence Techniques" *The Proceedings of the Sunderland Advanced Manufacturing Technology International Conference,* Sunderland Polytechnic, April, Section 2.1.

Palmer, G J, Kelly, P F and Weston, W, (1992) " Using Artificial Intelligence to Raise the Level of Abstraction in Process Planning" *The Proceedings of the Ninth Conference of the Irish Manufacturing Committee,* University College Dublin, Ireland, September, pp. 765-773.

Park, J Y and Khoshnevis, B, "A Real-Time Computer-Aided Process Planning System as a Support Tool for Economic Product Design, *Journal of Manufacturing System*, Vol.12, No.2, pp.181-192, 199?.

Pena-Mora, F, Sriram, R D, and Logcher, R., "Conflict Mitigation System for Collaborative Engineering" *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 9, 101-124, 1995.

Pham, D T and Gologlu, C, (1997) " Machining Set-up Planning Based on Evaluation of Feature Relations and Fixturing Constraints", *Application of Artificial Intelligence in Engineering* XII, RA, Adey, G. Rzevski and R. Teti (Eds) Computational Mechanics Publications, Southampton, Boston, pp. 35-38.

Ping, L, Yonton, H, Bode, J and Shouju, R " Multi-agent System for Cost Estimation" *Computer Ind. Engng*., Vol.31, No.3/4, pp. 731-735, 1996.

Prasad, B, Morenc, R S and Rangan, R M, (1993) " Information Management for Concurrent Engineering: Research Issues" *Concurrent Engineering: Research and Applications*, Vol.1, No. 1, pp. 3-20.

Prasad, B, Wang, F and Deng, J, (1997)" Towards a Computer-Supported Co-operative Environment for Concurrent Engineering" *Concurrent Engineering: Research and Applications*,Vol.5, No. 3, pp. 233-251.

Sapuan, S M and Abdalla, H S (1997), " A Prototype Knowledge Based System for Material Selection of Polymeric Based Composite for Automotive Components, *Composites A: Applied Science and Manufacturing,* 00, pp. 1-12, 1997.

Schrage, D P, (1992) "Concurrent Design: A Case Study", in *Concurrent Engineering: Automation, Tools, and Techniques*, pp.535-581.

Seif, M A, (1998) " A Concurrent Engineering Approach for Product Design Optimisation" *Concurrent Engineering: Research and Applications*, Vol.6, No. 2, pp. 101-111.

Shaikh, M A and Hansotia, B J, (1992) "Minimisation of drilling cost: a closed-form solution" *Computers and Industrial Engineering*, Vol.23, No.1-4, pp.443-446.

Sheng, P and Srinivan, M, (1995) "Multi Objective Process Planning in Environmentally Conscious Manufacturing: A Feature Based Approach, *Annals of the CIRP*, Vol. 44, No.1, pp. 433-437.

Sheu, L.C., Lin, J.T., "Representation Scheme for Defining and Operating Form Features", *Computer-Aided design*, Vol.25, pp. 333-347 (1993).

Skalak, S C, (1998) "Annealing a Genetic Algorithm over Constraints", http://vlead.mech.virginia.edu/publications/shenkpaper/shenkpaper.html.

Smith, P, "Expert System Development in Prolog and Turbo-Prolog", Sigma Press, 1990.

Stader, J and Jarvis, P, (1998), " Intelligent Support for Enterprise Modelling", The 13th Biennial European Conference on Artificial Intelligence (ECAI-98), Brighton Center, Brighton, UK, August-1998.

Subramanyam, S (1989), "A Co-operative Product Development Environment to Realise the Simultaneous Engineering Concept", Ph.D. dissertation, Department of Mechanical Engineering, University of Illinois, Urbana-Champaign.

Sun Common Lisp 4.0 Object System Guide, 1990.

Suri, R and Otto, K " Concurrent Part and Process Design for Quality Improvement" *The Proceedings of 1998 DETC: 1998 ASME Design for Manufacturing Conference*, Atlanta, September-1998.

Taiber, J G "Development of an optimisation method for determination of process sequences considering prismatic workpieces" *Computers in Engineering*, Vol.1, pp.271-280, ASME 1994.

Tappeta, V R and Renaud, E J (1997) "A Comparison of Equality Constraints Formulation for Concurrent Design Optimisation" *Concurrent Engineering: Research and Applications*, Vol.5, Number.5, pp. 253-261.

Thurston, D and Carnahan, J "Intelligent evaluation of designs for manufacturing cost" in Kusiak, A (Ed.), *Concurrent Engineering: Automation, Tools, and Techniques*, John Wiley, New York (1993), pp. 401-436.

Vancza, J and Markus, A, "Experiments with The Integration of Reasoning, Optimisation and Generalisation in Process Planning", *Computers in Engineering*, Vol.1, pp.243-251, ASME (1994).

Velay, X and Tabeshfar, K, (1995) " A Computer Adviser for Integrated Design and Manufacture" *The Proceedings of the Thirty-first International MATADOR Conference*, UMIST, Manchester, pp.137-142, April-1995.

VM User Workshop Report, 1994, http://www.isr.umd.edu/Labs/CIM/vm/lai1/final6.html.

Wang, F-C and Wright, P K, (1996) "A Multidisciplinary Concurrent Design Environment for Consumer Electronic Product Design" *Concurrent Engineering: Research and Applications*, Vol.4, No. 4, pp. 347-359.

Watts, T, Swann, P G M and Pandit, N R, (1998), " Virtual Reality and Innovation Potential" *Business Strategy Review*, vol. 9, no. 3, pp. 45-54(10).

Weston, R H, (1998), "Integration infrastructure requirements for agile manufacturing systems", *Journal of Engineering Manufacture*, September 1998, vol. 212, no. 6, pp. 423-437(15)

Wujek, B A, Renaud, J E and Batill, S M, (1996), " Concurrent Subspace Optimisation Using Design Variable Sharing in a Distributed Computing Environment" *Concurrent Engineering: Research and Applications*, Vol.4, No. 4, pp. 361-377.

Xue, D., Dong, Z., " Feature Modelling Incorporating Tolerance and Production Process for Concurrent Design", *Concurrent Engineering: Research and Applications*, Vol.1, pp. 107-116(1993).

Yoshimura, M and Yoshikawa, K, (1998) " Synergy Effects of Sharing Knowledge During Co-operative Product Design" *Concurrent Engineering: Research and Applications,* Vol. 6, No. 1, pp. 7-14.

Zhang, H C and Zhang, D, "Planning and Production Scheduling: Overview, Analysis and Object-Oriented Modelling" *Integrated Product, Process and Enterprise Design*, edited by Ben Wang, Chapman & Hall, pp.342-391, 1997.

Zhang, Y F, Nee, A Y C, and Fuh, J Y H, "A Hybrid Approach to Computer-Aided Process Planning for Prismatic Parts", *Computers in Engineering*, Vol.1, pp. 437-441, ASME 1994.

Zhou, X, Yan, J, Jin, Y, Ma, D, and Ling, Z, "Representation of Manufacturing Environment and Structured Knowledge Base in A CAPP System" *The Proceedings of the Computers in Engineering Conference and the Engineering Database Symposium*, pp. 647-654, ASME 1995.

APPENDIX 1

PRODUCT DESIGN SPECIFICATION

1. An Example of A Manufacturing Cell

Capability:

Max production capacity: 1000 per shift

Min production capacity: 100 per shift

Max manufacturable height: 150 mm

Min manufacturable height (h): 10 mm

Max manufacturable length (l): 100 mm

Min manufacturable length: 10 mm

Max manufacturable width (w): 125 mm

Min. manufacturable width: 10 mm

Holes: ∅ 8 - 80 mm

Available Processes:

Drilling, EDM, Milling and Grinding.

Material Removal Rates of The Available Processes: EDM = 1000 mm^3/min for holes and slots; Drilling = 3500 mm^3/min; Milling = 4500 mm^3/min for slots and faces, and for holes similar to drilling.

Cost:

Target process cost: 50 pound (required by the designer)

Set-up times:

Set-ups: EDM=30 min; Drilling=20 min; Milling=20 min

2. Part

Quantity:

Lot-size: 90 per shift

Material:

Type: Grey cast iron (3.5 % C, 2.25 % Silicon, 0.65 % Manganese)
Hardness: 200 BHN

Dimensions:

h: 20 mm
l: 120 mm
w: 120 mm

Features:

1. Through holes:

Hole_1:

d: 10 mm

l: 20 mm

dimensional tolerance: -0.1 mm

+0.16 mm

surface finish: 6 μm

accessibility: yes

finish allowance: 3 mm

x_from the datum: 15 mm

y_from the datum: 15 mm

z_form the datum: -20 mm

location: face_1 (xy)

Hole_2:

d: 10 mm

l: 20 mm

dimensional tolerance: -0.1 mm

+0.16 mm

surface finish: 6 μm

accessibility: yes

finish allowance: 3 mm

x_from the datum: 105 mm

y_from the datum: 15 mm

z_from the datum: -20 mm

location: face_1 (xy)

Hole_3:

d: 10 mm

l: 20 mm

dimensional tolerance: -0.1 mm

+0.16 mm

surface finish: 6 μm

accessibility: yes

finish allowance: 3 mm

x_from the datum: 105 mm

y_from the datum: 105 mm

z_from the datum: -20 mm

location: face_1 (xy)

Hole_4:

d: 10 mm

l: 20 mm

dimensional tolerance: -0.1 mm

+0.16 mm

surface finish: 6 μm

accessibility: yes

finish allowance: 3 mm

x_from the datum: 15 mm

y_from the datum: 105 mm

z_from the datum: -20 mm

location: face_1 (xy)

3. Slots:

Slot_1:

d: 30 mm

l: 25 mm

radius (R): 5 mm

dimensional tolerance: -0.1 mm

+0.16 mm

surface finish: 6 μm

accessibility: yes

finish allowance: 3 mm

x_from the datum: 25 mm

y_from the datum: 30 mm

z_from the datum: -20 mm

location: face_1 (xy)

Slot_2:

d: 30 mm

l: 25 mm

radius (R): 5 mm

dimensional tolerance: -0.1 mm

+0.16 mm

surface finish: 6 μm

accessibility: yes

finish allowance: 3 mm

x_from the datum: 70 mm

y_fr/m the datum: 60 mm

z_from the datum: -20 mm

location: face_1 (xy)

APPENDIX 2 (PUBLISHED PAPERS)

A prototype constraint-based system for the automation and optimization of machining processes

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Abstract: This paper presents an intelligent design system that enables designers to consider at the early stages of the design process all issues associated with the product life cycle. The evaluation and optimization of machining processes are among the most important aspects of these issues, requiring the involvement of various types of information from the different aspects of the product life cycle. The representation of this information in efficient format is very important for carrying out different design tasks. In order effectively to manage information exchange within different design and manufacturing domains, it is necessary to provide an efficient and timely communication network system. Therefore, various critical tasks such as overall coordination, control, consistency and data integrity have to be considered in order to avoid costly design iterations. This research article has focused on the development of a prototype system for machining process optimization.

The system uses a combination of both mathematical methods and constraint programming techniques and provides designers with the evaluation and optimization of feasible machining processes in a consistent manner at the early stages of the design process. As a result, unexpected and costly design iterations, which result in wastage of a great amount of engineering time and effort, and in a longer lead time, can be avoided.

The development process has passed through four major stages. Firstly, an intelligent constraint-based design system for concurrent product and process design, including a machining process optimization module, has been developed. Secondly, the product features, processes, cost, time and requirements have been represented in the format of constraints, frames, objects and production rules in order to be utilized to accomplish different design tasks. Thirdly, rules for the selection and optimization of feasible processes for complex features have been written, and finally, an information management system, with a conflict resolution mechanism, has been developed to achieve consistency in information exchange and decision-making activities between the different design areas.

Keywords: concurrent engineering, process optimization, cost estimation, constraints, knowledge-based systems, feature-based design, object-oriented programming, design consistency, conflict resolution

1 INTRODUCTION

The product development cycle encompasses several aspects, including marketing, conceptual design, detail design, process selection and quality control. In each of these areas there is an opportunity for manufacturers to gain competitive advantages by the outperforming of others.

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The current trend forces companies to produce low-cost and high-quality products in order to maintain their competitiveness at the highest possible level. This can be achieved by the best use of manufacturing resources such as machine tools, cutting tools, labour and processes to minimize the amount of time spent adding cost. This results in an effective and fast response to market requirements. Concurrent engineering is a systematic approach to the integrated, concurrent development of a product and its related activities such as process selection, tooling and time/cost estimation in order to meet customer requirements. It is therefore necessary to achieve the concurrent involvement of various life cycle perspectives in the product development process.

Concurrent engineering allows the design team to consider the factors affecting product cost, lead time, manufacturability and selection and evaluation of machining processes. Since researchers have given little attention to manufacturing cost estimation and optimization, this recent research work has concentrated on optimization of machining processes as it plays an important role in cost reduction [1]. It has been reported that almost 70 per cent of total product cost is based on decisions made at the early stage of the design process [2].

The various requirements associated with the perspectives of the design process such as part features, feature–process relations, machine tools, cutting tools, cost and time have to be taken into consideration in concurrent product development to satisfy the market expectation. These requirements also have a direct impact on the cost effectiveness of the design.

Representation of these requirements is very important for effective use during the design process so as to prevent designers/manufacturing planners from being engaged in a time consuming iteration process and accomplish many tasks such as manufacturability analysis, process selection and process time and cost estimation. Constraint-based systems are useful tools that are used to model and handle design requirements. However, complex designs cannot be easily represented in the form of constraints and variables. These systems should also offer flexibility to enable designers to attach new databases to the system. In addition, they must include an information management system for handling any design conflicts or constraint violation.

An efficient and timely communication network system should be provided within different design and manufacturing areas so that effective management of those constraints can be achieved. Various critical tasks such as overall coordination, control, consistency, and data integrity have to be considered in order to prevent costly design iterations. This necessitates establishing local area networks (LANs) within the organization to achieve the integration of different design areas in a consistent manner. Such integration needs a strategy for conflict resolution and reaching a consensus decision based on the perspectives of all related domains. Several authors have carried out research work in the area of information modelling and management, including Abdalla [3], O'Grady *et al.* [4], Noble [5], Karacali and Bell [6], Balasubramanian and Norrie [7] and Lander and Corkill [8].

There is no doubt that a concurrent product development approach improves productivity and helps to design products that offer high quality, reliability and less cost. It also reduces design iterations, hence leading to shorter product lead times. Recent research work has been carried out in the area of developing methods and tools for the estimation and optimization of manufacturing costs [9–14]. A number of papers have examined feature-based models focusing on machining form features [1, 15]. Research work in activity-based cost estimation of components can be found in the work of Shaikh and Hansotia [16], Das *et al.* [17, 18], Luong and Spedding [19] and Pham and Gologu [20].

Manufacturability analysis is another important factor in the drive to reduce product costs. A number of methods were developed to enable designers and manufacturing planners to address this detailed analysis [21–23]. Existing approaches to process evaluation and optimization are generally limited to feasibility evaluation and optimization of particular geometric specifications and available process combinations and capabilities. The best use of available alternative processes and concurrent consideration of manufacturability analysis and process evaluation and optimization have not yet been fully exploited.

Since large amounts of information exchange within different design areas and decision-making activities are involved in the design process, it is essential to develop an information management system including a conflict resolution mechanism to deal with any disagreements arising from different domains of the product life cycle. Therefore, the focus in this research work is on achieving such optimization, integration and consistency.

2 PROPOSED CONSTRAINT-BASED SYSTEM FOR CONCURRENT PRODUCT DEVELOPMENT

The proposed model consists of a computer aided design (CAD) solid modelling system, user interface, design representation, consistency manager, constraint-based system, process optimization and manufacturability analysis, and various knowledge sources (Fig. 1). All of these elements interact with one another, subject to the type of information that is required. It provides the designer with a flexible access to any level of the design process.

The procedure for designing a component via this system requires the designer to interact with a CAD system to generate a component and its features. The product information obtained from this system is passed to the knowledge-base system (KBS) via the user interface. The KBS includes a number of rules for executing several tasks, constraints and information about various aspects of the design process. The user enters information associated with manufacturing resources and capabilities, together with other areas of the design process, as a set of constraints. Based on the information provided from the designer and other expertise, the system carries out various tasks. It begins with checking the manufacturing capacity, and then features and dimensions of the component. It continues with the selection of processes, machines and cutting tools, and then goes on to evaluate process time and cost. The system provides the designer with an evaluation of all the decisions associated with part design by using the rules developed in the knowledge-base system.

It uses information associated with the manufacturing of form features, machine tool and cutting tool data, material data, criteria and goals to generate feasible process plans. The system gives recommendations on a design that cannot be manufactured with the available manufacturing resources. Also, it allows effective conflict resolution strategy for design inconsistencies arising from different areas of the design process, and provides the designer with a user-friendly interface, including visual and textural results from the analysis. The elements of the proposed system are explained as follows.

2.1 Constraint-based system

Constraints exist in terms of relationships between different requirements of the product during its life time, which have an important effect on the product cost/time and quality. The constraint-based system is a tool for representing and handling these requirements and can be formulated as sets of constraints. Constraints are used to model the requirements associated with various life cycle issues for effective use during the design process. It includes constraints of different product life cycle perspectives and design variables, together with a constraint propagation module for ensuring design consistency within the constraint network. When a value is assigned to a variable of the component, the constraints propagation module checks the assigned value to see if it violates any constraints. A valid solution is reached by the satisfaction of all constraints. When a constraint violation exists, the user is informed of the violation and given a warning, followed by some alternative suggestions from which he/she has to make a selection. In the system, constraints are formulated as rules, variables, values and domain.

The proposed model covers most aspects of design and manufacturing constraints, which include process constraints, machine constraints, material constraints, tooling constraints, part constraints, material handling constraints and tolerance and surface finish constraints. The constraint-based system is also linked to a consistency manager, ensuring consistent information exchange in the constraint network.

2.2 Consistency management

The consistency manager has the responsibility for managing the decision-making process and dealing with conflict situations, and providing the user with justification of decisions made on design. When it detects conflicts, warning(s) are given to the user with reasons for the conflict. A suitable strategy for solving conflicts is applied by the system in order to ensure design consistency in the constraint network and design output. The consistency manager allows designers to take necessary actions against the problems by giving some suggestions and to observe the design violations via the user interface.

2.3 Design representation

The knowledge-base system toolkit KEE (Knowledge Engineering Environment, developed by Intellicorp.) has been used to represent and model the product life cycle requirements and the design model. Building the design model and those requirements in a systematic

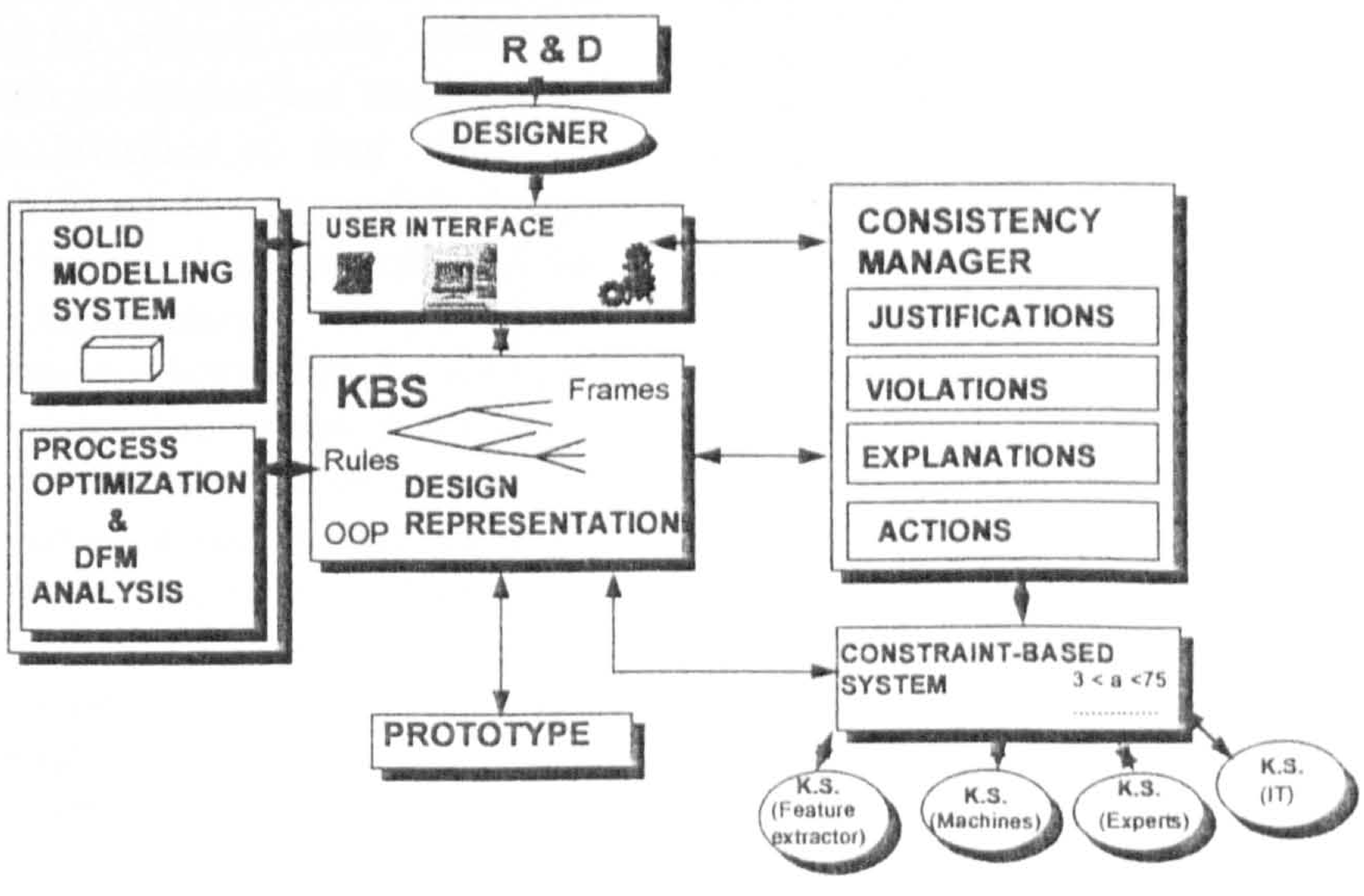

Fig. 1 Architecture of the concurrent product and process design paradigm

and well-organized way is essential in order to provide an effective interaction between the various design tasks such as design, manufacturing and tooling.

An object-oriented representation technique, frames, constraints and production rules have been used for the organization of knowledge. This consists of classes, objects, units, rules and/or methods with attributes inherited to all subclasses. The flexibility of these techniques enables designers to modify the existing objects or classes and add new units and attributes.

2.4 Process optimization and manufacturability analysis

This module has a rule-based algorithm for analysing the component and its features in order to select processes, machines and tools. The selected processes are then evaluated. The process times and costs of the components are estimated in order to ensure the manufacturability of the component. The system analyses processes and sequences and calculates the total machining cost of the product, including material, tooling, machining, overhead and labour costs. If the targeted process costs and times are not reached, then the system should be given advice from the designer to make modifications. This process will continue until a cost effective product is obtained. The rest of this paper discusses further details of how the process selection and optimization module functions.

2.5 User interface

To provide the user with an interactive design environment, a user-friendly interface has been developed as an important part of the expert system in order to enable the user to use the system easily and efficiently. KEE features such as menus and images were used to create the user interface so that the user-defined values can be obtained to accomplish design tasks. To enable the user to monitor constraint violations and value changes, active images are also incorporated in the user interface. Activating methods in slots by the use of a mouse was made possible by using the method actuators included in the user interface. In addition, the user interface enables users to interact with the CAD solid modelling system (Pro/Engineer) to generate three-dimensional solid models, add features and modify features and their attributes. The user communicates with the system using a superpanel, including menus, active images and method actuator, and results from the system are displayed in the Lisp listener, KEE output window and typescript window.

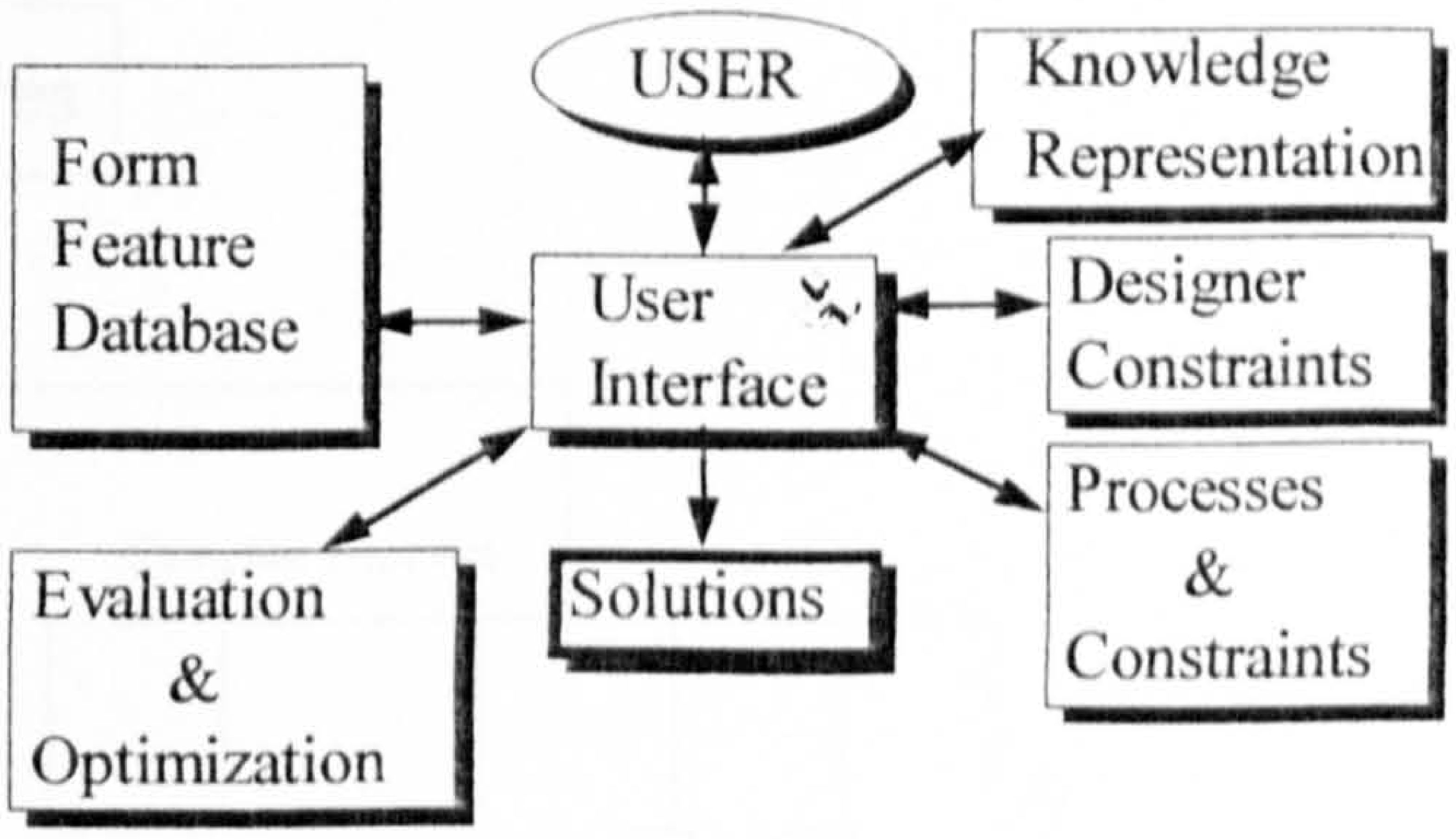

Fig. 2 Proposed model for the process of cost estimation and optimization

3 PROPOSED MODEL FOR PROCESS SELECTION AND OPTIMIZATION

As can be seen from Fig. 2, the proposed model consists of a form feature database, designer requirements, machining processes and constraints, an evaluation and optimization module and a user interface. Each module of the proposed system interacts with one another. The user interface provides the designer with the access to each module, and his/her requirements, formulated as a set of constraints (i.e. process time and cost, tool cost, set-up time and cost), will be the input to the system. For example, process costs, times and tool cost can be constrained by the predefined values provided by the user.

The form feature database was built to include various types of form feature. The selection of the feasible processes for the component is carried out using the form features and parameters retrieved from the form feature database.

Manufacturing information such as feature type, material, length and diameter ratio, cutting tool specifications, process availability, machine accessibility, process sequences, tolerances, surface finishes, optimum cutting parameters, cost and time were included in the processes and constraints module. Processes and constraints were also represented as hierarchies and objects in this module in order to evaluate and optimize the machining processes for a component. The system carries out an analysis of features of the component and then chooses the feasible machining processes for the component and calculates process times and costs, subject to the manufacturing constraints. For example, a component that has a form feature with a tight tolerance, special surface finish, and complex shape may need a machining centre to be manufactured by using a special cutting tool.

The required tolerance and surface finish of the feature could be obtained by a reaming and grinding process. Finally, the system, including a rule-based algorithm to evaluate the chosen processes based on

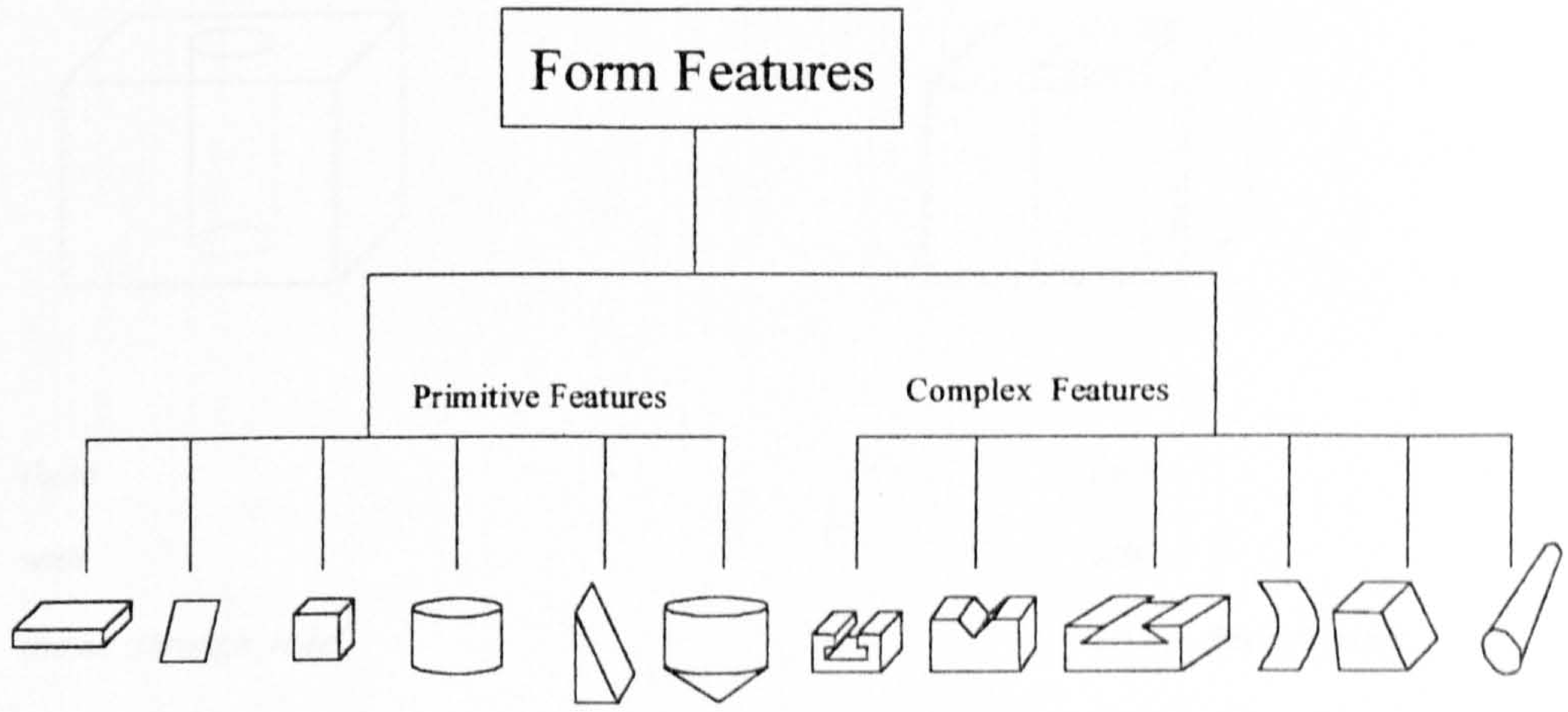

Fig. 3 Manufacturing form features

some criteria given in the design specification, calculates the total process time and cost of the component. If no process combinations are found acceptable, the system generates a dialogue including suggestions on the design, which the use has to take into consideration. This process can be continued until a set of feasible process combinations is obtained.

3.1 Feature representation

A feature is a generic entity which possesses product information and which may be used for design or communication in design, manufacturing and other engineering tasks such as assembly, manufacturing, process selection, cost/time estimation and maintenance. The representation of the features should be explicit in a form that matches manufacturing knowledge. Analysis of the form features directly associated with certain machining processes has an important effect on generating a detailed process plan. In this analysis, manufacturing form features are the lynch pin of the generation and optimization of machining processes and provide communication between designer and process planners to consider how their decisions can affect the product and process design. The use of manufacturing form features helps designers to simplify process planning without consideration of component manufacture in unlimited ways. Therefore, the feature-based representation technique has been used to represent the component and features in greater detail so that the designer, process and assembly planners or an expert system can use the same model to carry out various design tasks. Cost effective process planning can be achieved by the definition of manufacturing form features that are derivable from topological and geometrical description of the component. For example, a slot is a form feature defined by its parameters such as name, diameter, depth, locations, tolerance, process and surface finish. Based on these parameters the machining processes, set-ups, fixture and cutting tools can be chosen. The most common form features manufacturable on machine tools, and a three-dimensional model of an engine head composed of such features, are shown in Figs 3 and 4.

The proposed model contains production rules and knowledge about the form features and machining processes. These rules manipulate the behaviour of the feature and process data which are represented in a structured way and an effective format made to reach a feasible solution. Manufacturing environment capabilities (i.e. production size, maximum length, diameter, tolerance, surface finish and tools) are contained in the rules. Manufacturing form features are represented by using an object-oriented representation technique, as shown in Fig. 5.

3.2 Representation of design and manufacturing knowledge

Knowledge representation techniques used to represent

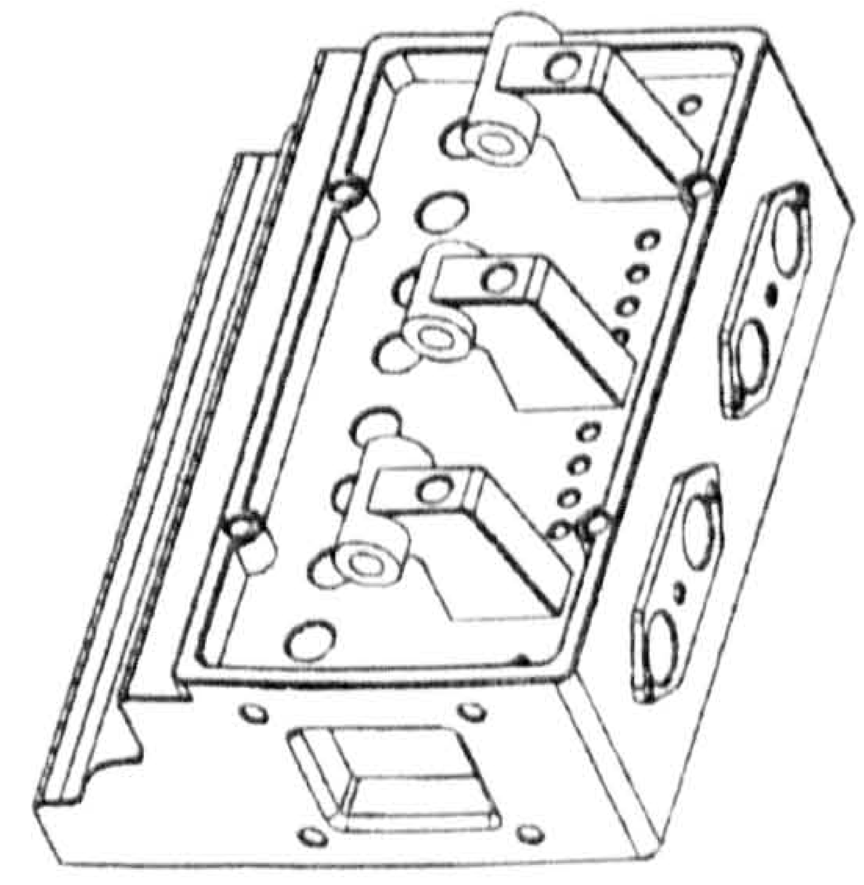

Fig. 4 Three-dimensional solid model

(hole

with

(name :through_hole)

(diameter :10 mm)

(depth: 40 mm)

(depth/diameter_ratio: 4)

(dimensional_tolerance: ±0.0001)

(x_distance: 100 mm)

(y_distance: 35 mm)

(z_distance: 0 mm)

(machining allowance: 3 mm)

(first_process: drilling)

(second_process: grinding) (.....................))

(slot

with

(name: through_slot)

(length: 15 mm)

(depth: 40 mm)

(positional tolerance: ± 0.01

(x_distance: 100 mm)

(y_distance: 35 mm)

(z_distance: 0 mm)

(radius :5 mm)

(machining allowance: 3 mm)

(first_process: milling)

(second_process: none) (......))

Fig. 5 Object-oriented representation of form features

design and manufacturing knowledge in this research are described in detail as follows.

3.2.1 *Constraints*

In the design process, there exists a huge amount of information from different aspects of the product life cycle in the form of design requirements, which have to be met by the designed product, and those requirements that can be represented as constraints. For instance, from a process planner's point of view, the tolerance of a hole could be a constraint or a customer could constrain the product cost. Constraints represent certain limitations or restrictions on design variables. Design and manufacturing variables can be effectively held in a slot or a rule class, and can be kept between certain values defined as constraints. In this research, design and manufacturing requirements are formulated as a set of constraints in slots of a unit and the production rules.

The various types of constrain used in this research are as follows:

(a) domain (i.e. machine tools, cutting tools, manufacturing capacity, etc.);
(b) equations [material removal rate (MRR) $= (\pi D t^2/4) f N$ or $8 \geqslant d \leqslant 80$ mm]
(c) production rules (*If* (*feature is hole and surface roughness* $\geqslant 6$) *then* (*process is drilling*))
(d) logical constraints (*Do you want to change the diameter?* (*YES* or *NO*))

Design and manufacturing variables are stored in the slot of an object, including working constraints. An example of how manufacturing requirements are formulated as constraints is shown in the following rules in which a form feature has its own variables (diameter, depth, lower_tolerance, upper_tolerance and surface_finish).

The lower_tolerance variable has its own constraint: (*lisp*(> = *?lower_tolerance 0.025*)), or the lower_tolerance of the feature must be equal or exceed the limit 0.025 mm. Figure 6 shows the flow chart of process selection for blind holes:


```
(slot_end_milling_rule_1
(if (?what is in block-slot)
(the length of ?what is ?length)
(the width of ?what is ?width)
(the depth of ?what is ?depth)
(the finish.allowance of ?what is ?finish.allowance)
(the  lower.tolerance of ?what is ?lower.tolerance)
(the upper.tolerance of ?what is ?upper.tolerance)
(the surface_finish of ?what is ?surface_finish)
(lisp (<= ?lower.tolerance  -0.005))
(lisp (>= ?upper.tolerance  0.005))
(lisp (>= ?surface_finish  0.8)
(.........)
then
(the volume of ?what is (lisp (- (* (* ?length ?width) ?depth)
(* (* (- ?length ?finish.allowance) (- ?width ?finish.allowance)) ( - ?depth ?finish.allowance)))))
(lisp (format t
"~%
==========================================================
                THE POSSIBLE PROCESSES TO BE EVALUATED
==========================================================
FEATURES                                       POSSIBLE PROCESSES
==========================================================
~D                                             MILLING
==========================================================
                                               EDM
==========================================================~%"
?what))
(the first.process.selection of ?what is ok)
(the possible.process_1 of ?what is milling)
(the possible.process_2 of ?what is edm)
(more rules)))
(slot_end_milling_rule_2
(if (?what is in block-slot)
(not (the first.process.selection of ?what is ok))
```

```
(the length of ?what is ?length)
(the width of ?what is ?width)
(the depth of ?what is ?depth)
(the finish.allowance of ?what is ?finish.allowance)
(the  lower.tolerance of ?what is ?lower.tolerance)
(the upper.tolerance of ?what is ?upper.tolerance)
(the surface_finish of ?what is ?surface_finish)
(……..)
then
(the volume of ?what is (lisp (- (* (* ?length ?width) ?depth)
(* (* (- ?length ?finish.allowance) (- ?width ?finish.allowance))
( - ?depth ?finish.allowance)))))
(the possible.process_1 of ?what is milling)
(the secondary.process of ?what is grinding)
(more rules)))
(the possible.process_1 of ?what is drilling/counterboring)
(the possible.process_2 of ?what is milling)
(the possible.process_3 of ?what is edm)
(………))))
```

3.2.2 Frames

Frames as a knowledge representation technique are used for storing interconnected information about a design and an object. Knowledge representation of stereotypical objects can be achieved effectively by using the frames consisting of a name and a number of slots. Various types of value [i.e. numerical (12, 24), logical (yes or no), procedural (methods) and symbolic (steel)] can be used in the slots. The frames of the KEE are very flexible so that images and active values to any slots can be attached to monitor value changes. Facets as attributes of slots (i.e. value class, inheritance role, maximum and minimum cardinality) allow description of values of a slot and how they are passed down the hierarchy. The example below shows how a product design specification can be represented in the form of frames:

```
(Blind_hole_rule_1
(if (?what is in blind_holes)
(the diameters of ?what is ?diameters)
(the depth of ?what is ?depth)
(the lower_tolerance of ?what is ?lower_tolerance)
(the upper_tolerance of ?what is ?upper_tolerance)
(the surface_finish of ?what is ?surface_finish)
(……..)
(lisp (>= ?lower_tolerance 0.025))
(lisp (>= ?upper_tolerance 0.15)
(lisp (>= ?surface_finish 1.6)
(……..)
then
(lisp (format t "****The possible process for ~d is
drilling, end_milling and edm..****" ?what))
(the volume of ?what is (lisp (* (* (/ π 4)
 (* ?diameters ?diameters)) ?depth)))
(the first.process.selection of ?what is ok)
```

```
Superclass: Product Specification
Subclasses: Part, Manufacturing Cell Capacity, Available Machine Tools

Properties: (part type

(value ((lambda (self)
(with-keeio (setq choice (prompt-use 'choice-multiple
:choices '(rotational non-rotational)
:prompt "Please select one: "
:few-choices-mode 'menu))))))
(inheritance method)
(valueclass (#[Unit: method keedatatypes])) (default nil)
(activeimage(#[Unit:windowpane-availability-of-machine.constraints.
manufacture007])
. unique.values) (cardinality.min (1)) (cardinality.max (1)))

(length…..)
```

3.2.3 Production rules

Knowledge and facts about a problem domain can be represented as a rule of the form ***IF*** premises ***THEN*** conclusion. The production rules are very effective for storing design and manufacturing constraints in the production rules. The proposed model uses production rules as values of unit attributes (slots) to be manipulated and inherited from higher classes to subclasses. The production rules included in slots enable a complex structured rules system to interact with different sets of rules associated with different units. A combination of these rules with methods, which are LISP functions stored as a value of a slot, allows the rule system to run fast and efficiently. As an example, in the *prototype-testing-rule-1* shown below, total manufacturing cost is calculated by using a LISP function as shown in the rules set out below.

The command *UNITMSG* sends a message to the *total cost* method in the *part* unit to perform the calculation of the total process cost. The calculated value will be the new value of the *total_manufacturing_cost* slot:

```
(prototype-testing-rule-1
(if (the total_m_cost_control of part is ?total_ m_cost_control)
(?total_ m_cost_control = ok)
then
(the total_manufacturing_cost of part is (lisp (unitmsg 'part 'total-cost)))))
(prototype-testing-rule-2
(if (the total_manufacturing_cost of part is ?total_manufacturing_cost of part)
(the target_manufacturing_cost of part is ?target_manufacturing_cost)
(lisp (>= ?total_manufacturing_cost of part ?target_manufacturing_cost))
then
(lisp (format t "~%The estimated manufacturing cost of part is higher than the proposed target
manufacturing cost. The target manufacturing cost is ~D $ and the estimated manufacturing cost is ~D
$..~%"
?total_manufacturing_cost
?target_manufacturing_cost)))
(prototype-testing-rule-3
(if (more rules))))
```

3.2.4 Object-oriented programming

The object-oriented programming technique enables designers to model real world concepts as objects which are collections of data grouped together in terms of similarities in their structure and behaviour [**24**]. By using this technique, design and manufacturing objects such as machine tools, cutting tools, features, material features and machining elements are organized into various classes represented in hierarchies (Fig. 7).

A class has a name and several subclasses (consisting of a number of objects) with a number of slots (attributes such as capacity, power, feed rate, size and tolerance). All classes can be broken down into subdivisions so that all components of the class are considered. An object or a member of a class (i.e. machines, cutting tools and materials) can be added to a subclass to represent the available manufacturing resources of a company. Inheritance is an important characteristic of the object-oriented programming technique. It enables the designer to define a specific value in a higher class to be inherited by the lowest class of the hierarchy.

3.3 Problem-solving techniques

A model of the knowledge base is built to use information about different domains to carry out various analyses. However, the proposed system needs problem-solving techniques and reasoning heuristics in order to find answers to the queries passed by the designer. Object-oriented programming, production rules and the

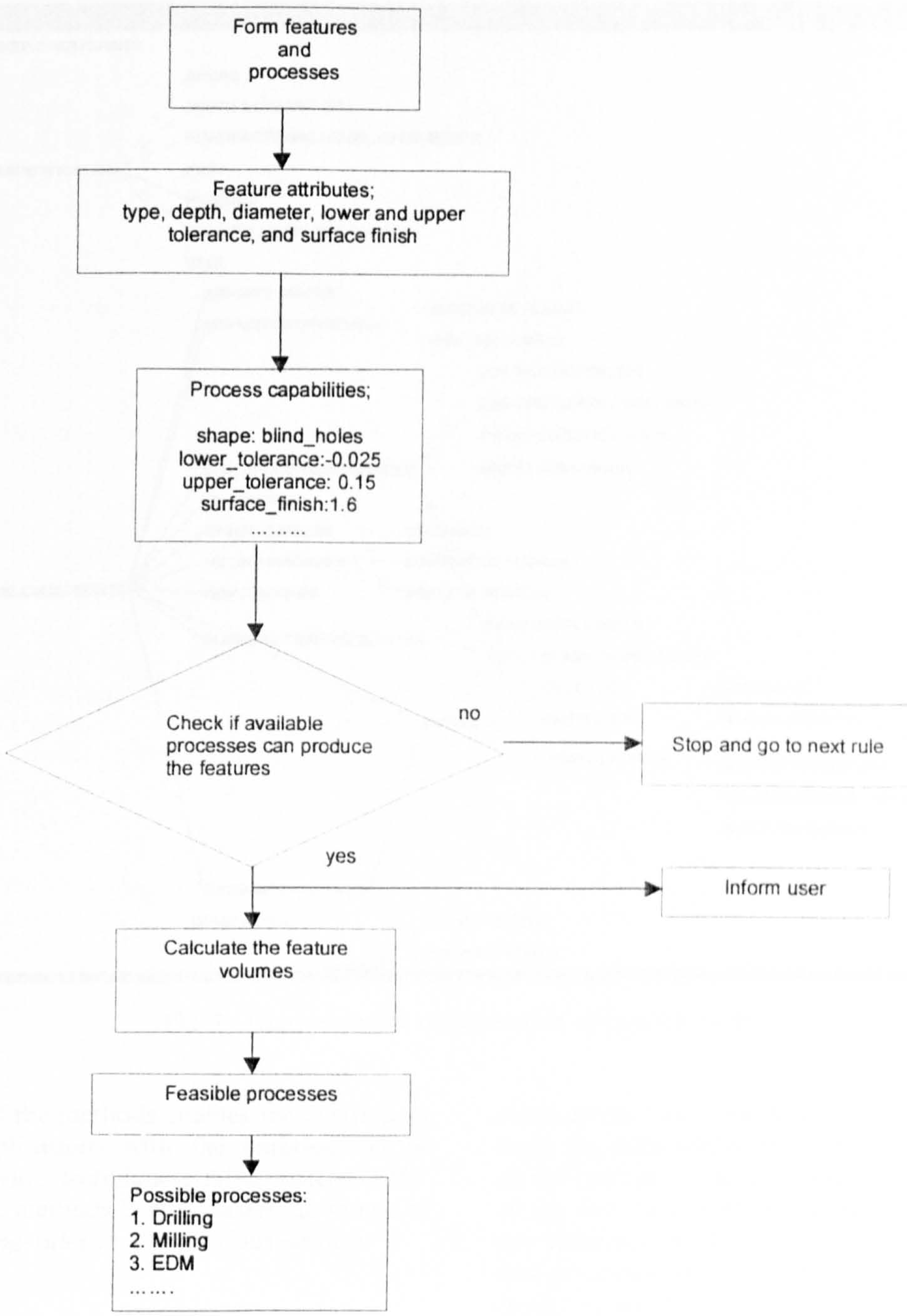

Fig. 6 Flow chart of process selection for a blind hole

combination of these techniques are used for problem solving in the developed system.

3.3.1 *Object-oriented programming (OOP)*

As mentioned in the previous section, knowledge bases consist of objects, which can carry problem-solving behaviour in the form of a LISP function stored in the *total_cost* slot of the *part* object as shown in Section 3.2.3. The behaviour or a function of the method (which includes the LISP function) is stored inside objects of the knowledge bases. The LISP functions in the method slots accomplish the given tasks such as time/cost calculations of a component. This is shown as follows:

```
(total_cost

(value

((lambda (thisunit)

(let ((cost_values (get.values 'part 'total_m_cost)))

(apply # ' + cost_values)))))

(inheritance method)

(valueclass (# [Unit: method keedatatypes]))

(default nil))
```

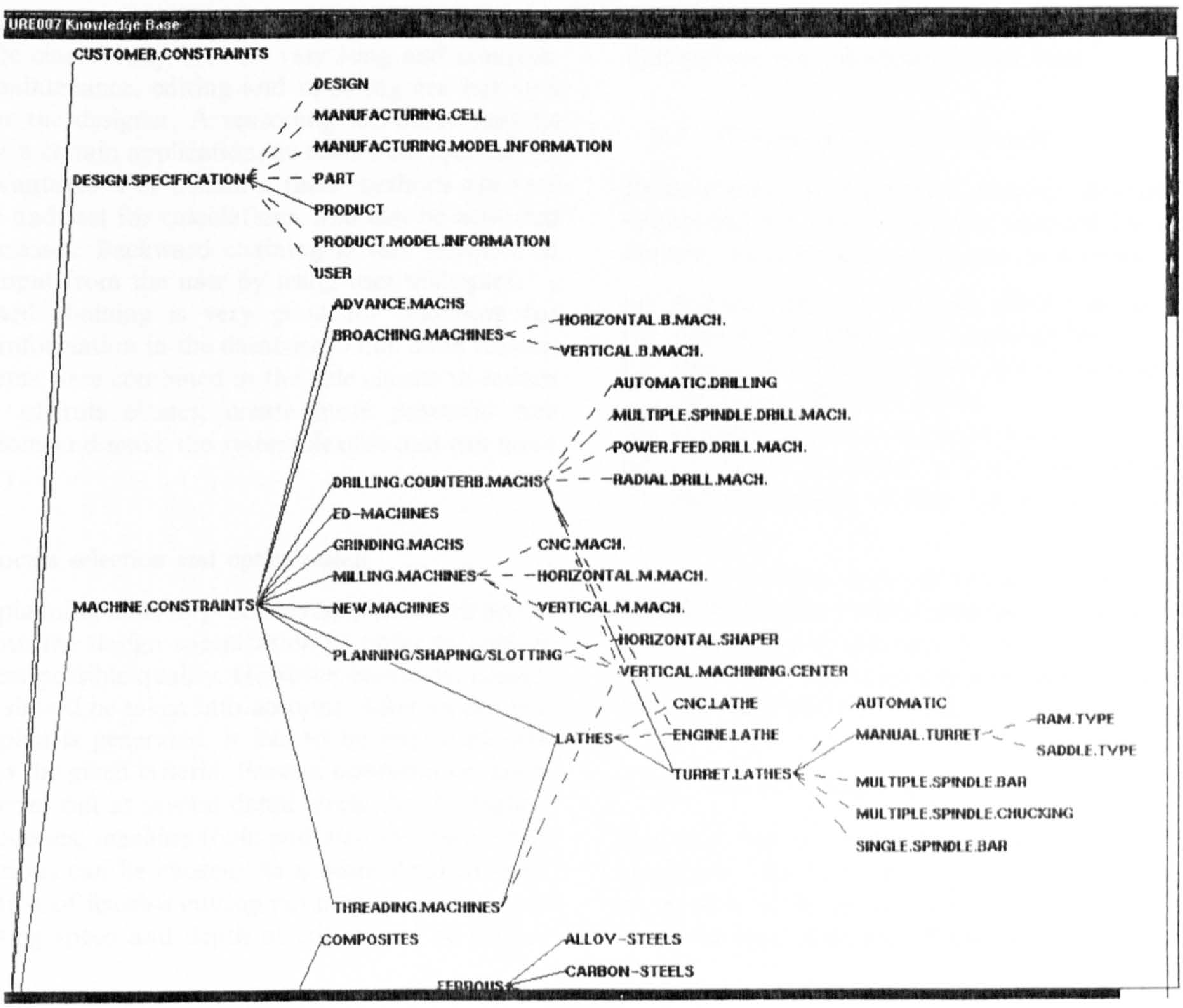

Fig. 7 Object-oriented representation of machine tools

The flexibility of the methods enables the creation of powerful rule applications with the combination of other problem-solving techniques. Also, special LISP commands activate methods in rule classes, as shown in the *prototype-testing-rules* in the previous section.

3.3.2 *Production rules*

Production rules are also used for reasoning. Several rules take the expert from an intermediate conclusion to a more precise conclusion. In the proposed system, several rule classes have been developed and connected to each other, namely the conclusion of one rule is included in the premise of another rule. This is called chaining. When chaining commences, conclusions of one rule class match premises of another rule class. Chaining is used either in a forward or backward direction.

3.3.2.1 Forward chaining. Forward chaining tries to find implications of new information. It generally starts from the input of new data from the user or from a different domain of the knowledge base. It is called event-driven or data-driven reasoning. The system scans the rules whose premises include the new fact. If all the premises of a rule class are true, the conclusions of the rule class will be asserted in turn and become new information. The system then searches for the rule that possesses this new information as a premise, and checks to see if all premises of this rule are true. This process continues until no rules are found with the matching premises.

3.3.2.2 Backward chaining. Backward chaining tries to verify a given fact or hypothesis. As backward chaining starts with the goal of proving something, it is termed goal-driven. The system scans the rules whose conclusions match the fact to be verified. The fact is found to be verified if all the premises of the rule class in question can be verified in turn.

3.3.3 *Combination of the problem-solving techniques*

In this research work, the combination of the above-mentioned techniques are used in the same rule classes effectively. Using only one technique is not sufficient to carry out the design tasks in a reasonable time. Therefore, rule classes may become very long and complex. Thus, maintenance, editing and updating are not easy tasks for the designer. A reasoning technique may be good for a certain application, as each technique has its own advantages. For instance, these methods are very effective and fast for calculations, and can be activated in rule classes. Backward chaining is very effective to obtain input from the user by using user dialogues.

Forward chaining is very good for searching for specific information in the database. Thus these reasoning systems were combined in the rule classes to reduce the size of rule classes, create more powerful rule applications and make the system flexible and run more efficiently.

3.4 Process selection and optimization

Process planning aims to produce components in accordance with the design specification in order to achieve the highest possible quality. However, economic considerations should be taken into account. After an optimal process plan is generated, it has to be improved with respect to the given criteria. Process optimization needs to be carried out at several detail levels. At the highest level, processes, machine tools and also the sequencing of operations can be chosen. At a more detailed level, the selection of feasible cutting parameters such as feed rate, cutting speed and depth of cut should be carried out. Also, process times and costs of processes, tools and set-ups are calculated at this level.

3.4.1 *Criteria for process selection*

Process selection requires a number of criteria to be considered for feasible process selection for each form feature. Some criteria are shown as follows:

(a) feature type: *through hole, blind hole, and slot*;
(b) material: *hardness and machinability*;
(c) length and diameter ratio: *8/1 for twist drilling, 5/1 for boring, 20/1 for EDM*;
(d) availability: *YES/NO from user*;
(e) tolerance: *broaching* ± 0.025 *and boring* ± 0.04;
(f) surface finishes: *drilling 1.6–6.3 and reaming 0.8–3.2.*

As an example, some of the above criteria are contained in rules for process selection as shown in Section 3.2.2 for process selection for a blind hole. Further details of the process selection procedure are available from the authors on request.

3.4.2 *Process evaluation*

The material to be used for the component has an important effect on the selection of the machining parameters such as tool material, cutting speed, feed rate and tool diameter. These machining parameters

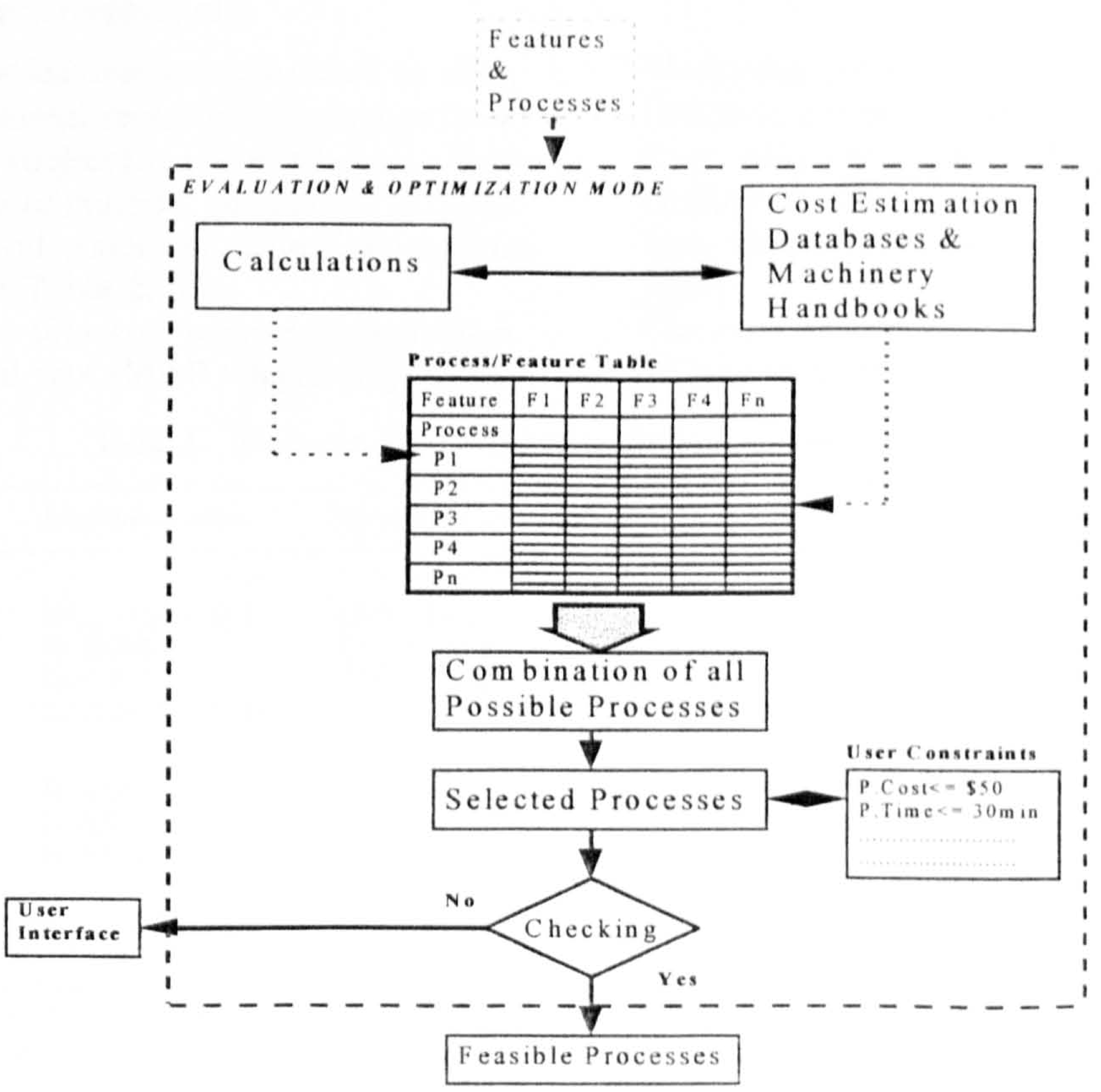

Fig. 8 Optimization approach

have to be left out of the table. A rule-based algorithm was developed to deal with this problem, and is presented later. The system also allows the users to define the maximum allowable cost and time for the candidate processes of a feature. This makes the system very flexible in keeping the total process cost and time of the part or a single form feature to the predefined values.

Then, the system evaluates the set of process combinations or possible processes for the form features of the component by comparing process cost and time and the other variables against the user's requirements. Feasible processes will be those that meet the user's requirements. One of the feasible process combinations is selected as a solution, or further evaluation can be carried out. Specific constraints (i.e. process cost and time) can be changed to obtain a feasible solution unless any process combinations satisfy user requirements. Changing the constraints also enables a process combination to be obtained if necessary. In addition, the user interface informs the user of results of the process selection.

3.4.3 *Process time and cost estimation*

The calculation of process time and cost is carried out using standard formulae. As the proposed approach uses feature-based cost estimation and optimization of machining processes, the following formulae were used for the estimation of process time and cost:

$$\text{Process time} = \frac{\text{form feature volume}}{\text{material removal rate}} \tag{1}$$

The volume of the form features was calculated by using standard formulae. Material removal rates change from one process to another, subject to certain criteria (i.e. tool diameter and type, type of material and cutting parameters). Material removal rates of some machining processes are shown in Table 2.

Reductions in process time/cost require maximization of the material removal rate (MRR) depending on the following parameters:

$$T_l = T_{l\max} \quad \text{(tool life)}$$

$$D_t = D_{t\max} \quad \text{(tool diameter)}$$

$$f = f_{\max} \quad \text{(feed rate)}$$

$$V = V_{\max} \quad \text{(speed)}$$

$$W = W_{\max} \quad \text{(depth of cut)}$$

Cutting parameters (i.e. cutting tool diameter, feed rate, spindle speed and depth of cut) should have maximum values to maximize the MRR. Also, cutting tool selection has to be taken into account. In addition, properties of the selected material, such as hardness, machinability and electrical conductivity, affect the cutting parameters. MRR for any processes is calculated using the related formulae after suitable cutting tools have been selected in order to meet material requirements. The estimated process time/cost for producing the form features is then calculated. The values of the productive hour cost (PHC) for various processes from the cost estimation databases have been used to calculate process costs.

Total process cost is calculated by using PHC values as follows:

$$\text{Total process cost} = \text{lot time} \times \text{PHC} \tag{2}$$

Lot time has to be calculated subject to the quantity of part or form features. A list of some of the PHC values (US$/h) for processes including set-up costs is shown below:

Machining centre	12.53
Drill/counter bore/ream	11.64
Face, side, slot, form, end	12.20
Drilling machine set-up	10.84
Tool life and replacement	11.25
EDM	12.05
Chemical machining	9.67
Milling machine set-up	12.10

Table 2 Formulae for estimation of process related concern [**31**]

Processes	Machining time	Spindle power	Tool life	Material removal rate	Form feature volume
Conventional					
Drilling	$2(l_{max}/V_f)k+2l/V_f$	$TN/63\,030\eta_m$	—	$(\pi Dt^2/4)fN$	$\pi D^2/4h$
Rough milling	Fv/MRR	$F_cV_c/33\,000\eta_m$	$C/V^\alpha f^\beta a_p\gamma$	Wa_pfnN	Feature volume
Finish milling	Surf$/V_f\Omega$	$F_cV_c/33\,000\eta_m$	—	Wa_pfnN	Feature volume
Grinding	$LT_sDia/(WiP)2f_i\pi V_g$	—	—	$\pi fDiaP$	Feature volume
Non-conventional					
EDM	Fv/MRR	—	—	49 cm^3/h*	Feature volume
Electrochemical machining	Fv/MRR	—	—	Max. 1000 cm^3/h*	Feature volume
Laser beam machining	Fv/MRR	—	—	Average 0.4 cm^3/h*	Feature volume

Definitions: l_{max} = maximum drilling depth; T_s = total stock removed from the diameter f; V_f = feed rate; N = spindle rotational speed (r/min); k = index for the number of drilling cycles; D = diameter; Dt = tool diameter; Fv = feature volume; l = length of the hole to drilled; η_m = machine efficiency; h = depth; MRR = material removal rate; F_c = cutting force; C = a constant determined by the geometry of the hole, tool material and part material; V_c = cutting speed; a_p = depth of cut (in); γ, α, β = coefficients, W = width of cutter; n = number of teeth; L = length of the part grind; T = torque; Dia = original diameter; Wi = width of the grinding wheel; P = traverse for each work revolution in fraction of wheel width; f_i = infeed of wheel per pass; V_g = workpiece peripheral velocity; Surf = feature surface; Ω = overlapping factor, cutting depth for circumferential milling and width of cut for face milling.

* MRR is subject to characteristics of materials (type, hardness, electrical conductivity, etc).

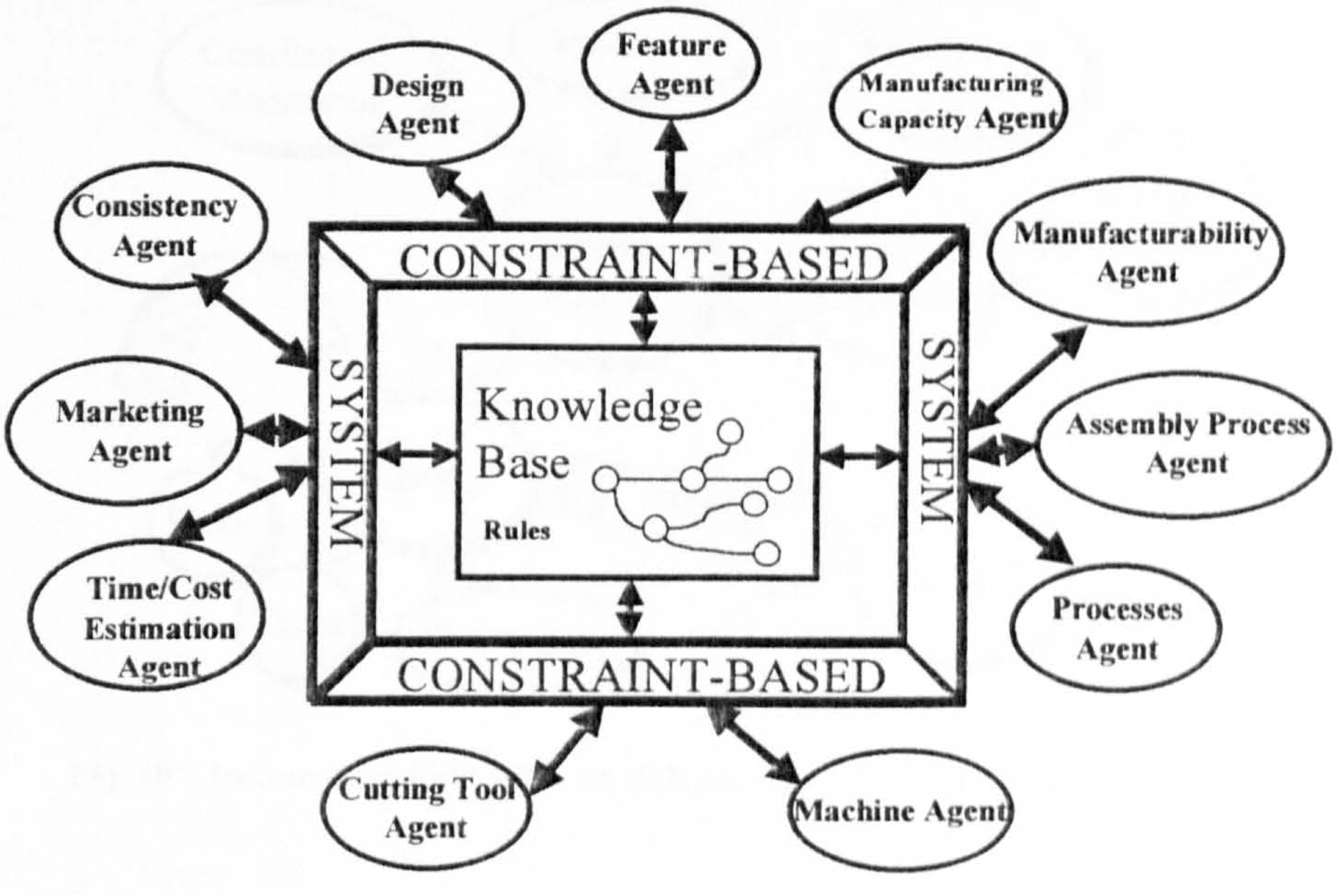

Fig. 9 Overall design consistency in the system

Boring and facing	13.16
Surface grinding	11.25
Vertical internal grinding	11.25
Horizontal milling, drilling, boring	13.16
Chemical machining	11.49
Travelling wire electrical discharge machining	12.05
Die casting	11.57
Injection moulding	11.07

Using the above figures, the total cost is formulated as follows:

$$\text{Total cost} = \text{material cost} + \sum [(\text{lot time} \times \text{PHC}) + \text{tool cost} + \text{set-up cost}] \quad (3)$$

Set-up times for various machine tools are available in machining handbooks and were used to estimate set-up costs to obtain a more accurate cost estimation [**25**, **26**, **28**].

3.5 Information management and design consistency

Different design tasks (i.e. material selection, manufacturability analysis, process selection and optimization) need a huge amount of information to be accessed and shared in the knowledge base so that they can be carried out. This also necessitates the addition of new information to the knowledge base used to carry out such tasks. As seen from Fig. 9, several agents representing the life cycle aspects of the product have their own tasks to carry out. They have a common knowledge base to access necessary information.

Agents as an entity are capable of solving locally generated problems through communication with other agents [**29**]. They have responsibilities for solving a given task in a design problem such as process selection and capacity checking. Agents should include a limited amount of program for dealing with the given subtasks in order to execute each task faster and at less cost. Also, they will be created or modified easily when necessary. Agents should interact with one another and exchange information in order to accomplish their own task. In order to ensure consistency in the constraint network, any new information from users or agents is propagated by the constraint-based system. This checks to see whether or not the new information causes constraint violation. Agents share information, while consistent information flow is achieved in the system. This is shown in Fig. 10.

An agent has to access the design input from the knowledge base in order to accomplish its task. A design input that violates any constraints of the agent will be detected by the consistency agent. A message will then be sent to a method carrying a small program, which is a function of LISP responsible for conflict resolution. Alternatives will be presented to the users by a menu from which a design agent has to be selected. Alternatively, the system may ask the user to write his/her answer at the user prompt by giving necessary explanations. The new information does not violate the constraints of the agent and is included in the knowledge base in order to be utilized by other agents whenever required. The user interface informs the user of conflicts immediately. For instance, in the system,

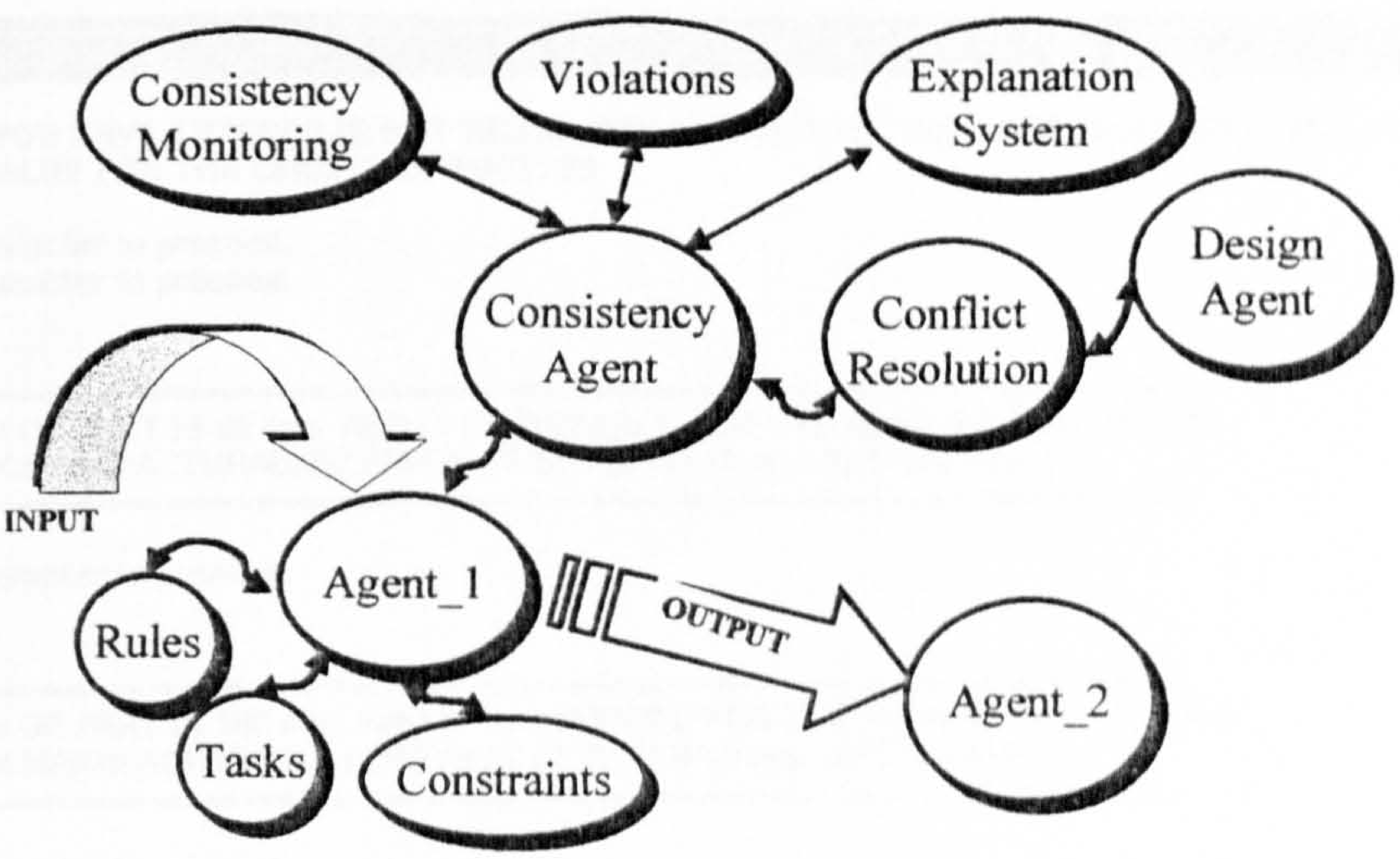

Fig. 10 Information flow between different aspects of the product life cycle

the manufacturing capacity agent contains constraints on the production capacity. If a production quantity defined by the user is not between the constraints, the user will be informed by the user interface and a number of alternative solutions for sorting out this problem will be displayed.

The user will have to select from the suggested alternative or type an answer at the prompt window as shown in Fig. 11. The production quantity required by the user will be consistent information in the system if it does not violate the constraints of the manufacturing capacity agent. By using this system, consistent information flow between different tasks of the product life cycle is achieved without costly design iterations caused by conflicts in the design process.

3.5.1 *Consistency monitoring in the system*

As part of the design consistency approach, the system enables the designer to monitor inconsistencies in the system. This provides the designers with visual displays of constraint violation. In the developed system, design variables are restricted by sets of constraints, which are represented in terms of rules, frames and intervals.

The knowledge engineering environment (KEE) offers various types of image that can be used to change their attributes (colours, shapes and texts) subject to the alarm values to be highlighted and watched by the designers. However, this does not give enough information about inconsistencies. An explanation system is incorporated in the system to inform the designers of reasons for the violated constraints shown on the design consistency control panel. The typescript window is used for this purpose. When the system detects any inconsistency, it is shown on the panel, and then reasons for the conflict are given in textural format in the typescript window (Fig. 12).

3.6 User interface

In order to provide good interaction between the system and the user, a user-friendly design environment was developed. The development of the user interface was carried out using KEE toolkit and other Lisp programmes. KEE as an expert tool kit has good facilities for developing interactive user interfaces. The specification of the user interface was initially defined by Berrais [**30**]. The developed user interface is shown in Fig. 13 and consists of three major elements. The first element is the concurrent engineering menu, including a design for maunfacture (DFM) button which activates a multiple choice menu for carrying out design tasks such as process selection, cutting tool selection and cost/time estimations. It also includes buttons for loading necessary files and starting the system and resetting the databases. In addition, there is a help menu for the user. By using a mouse, the menus and buttons can be easily activated. The second part of the user interface is the design consistency control panel on which various active images are placed and linked to the design variables. The active images change their attributes such as text and colour to show the design inconsistencies. Any changes made to the variables are reflected on the images linked to them. The third element of the user interface is the typescript window which provides the designers with textural displays of the reasons for the conflicts, results of the analysis carried out, suggestions for the resolution of the conflict and prompts for answers and queries.

3.7 Process optimization scenario

The optimization of machining processes should be carried out after a number of design analyses (i.e. manufacturing cell capability, feature types, dimensions and tolerances subject to production quantity, available

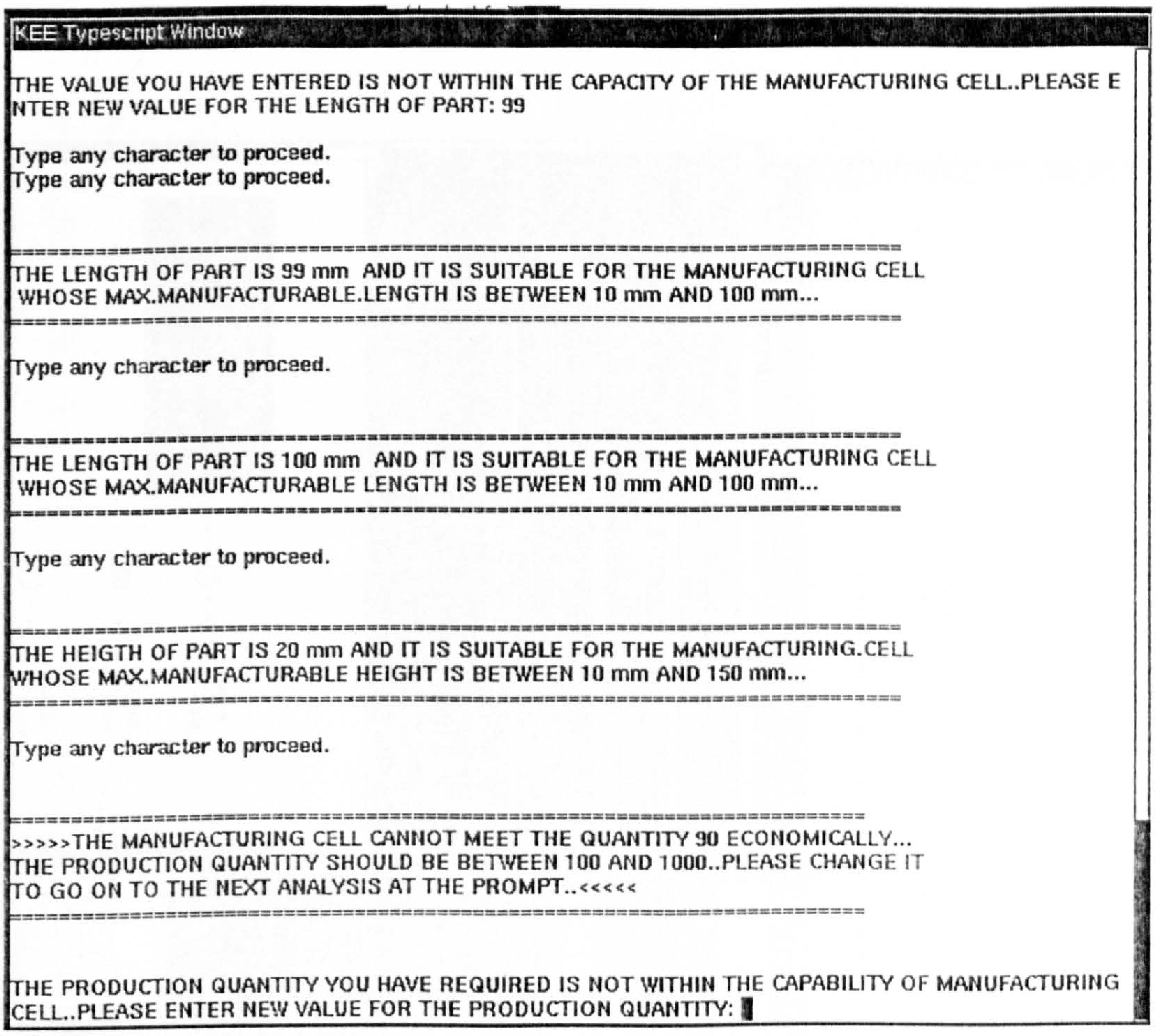

Fig. 11 Conflict resolution

processes and their constraints). The rule-based algorithm for the evaluation and optimization of the machining processes consists of two major steps: machining process selection for the component and the optimization of these processes. Steps 1 to 4 select the feasible processes for each form feature according to material, lot size, tolerance, surface finish and feature type. The other steps include the accomplishment of various tasks (i.e. selection of suitable cutting tools, machine tools and optimum cutting parameters, and calculations of process variables such as MRR, lot time, set-up cost and tool cost). Comparison of the selected feasible processes subject to the process variables is also carried out. The different steps and tasks involved in the process optimization process are shown in detail in Fig. 14:

1. Select a material from the database.
2. Get the lot size of part or features.
3. Get a form feature from the part.
4. Select feasible processes for the feature, satisfying requirements of the part (tolerance, surface finish, feature type, etc.).
5. Take one of the possible processes.
6. Select the biggest possible diameter, shortest length and available and cheapest cutting tools for the selected process.
7. Select available machine tools and fixtures.
8. Select optimum cutting parameters: depth of cut, cutting speed, feed rate and cooling conditions.
9. Calculate feature volume MRR, lot time, tool cost for the lot size and set-up cost for the process.
10. Calculate total cost and time of the process.
11. If there are possible processes left to be analysed,
12. Go to 5 or else go to 13.
13. Compare the possible processes for each form feature with each other and eliminate the processes that have higher tool, process and set-up cost and time values than others.
14. If there is only one process for the form feature, consider it to be the most feasible process or else ask the user to select one process from the following list:
    (a) If there are form features left to be analysed,
    (b) Go to 3 or else 17.
    (c) Calculate the final process cost of the part.
    (d) Inform the user.
    (e) End.

The design of a cylinder head has been evaluated by the developed system as shown in Fig. 4. The results drawn

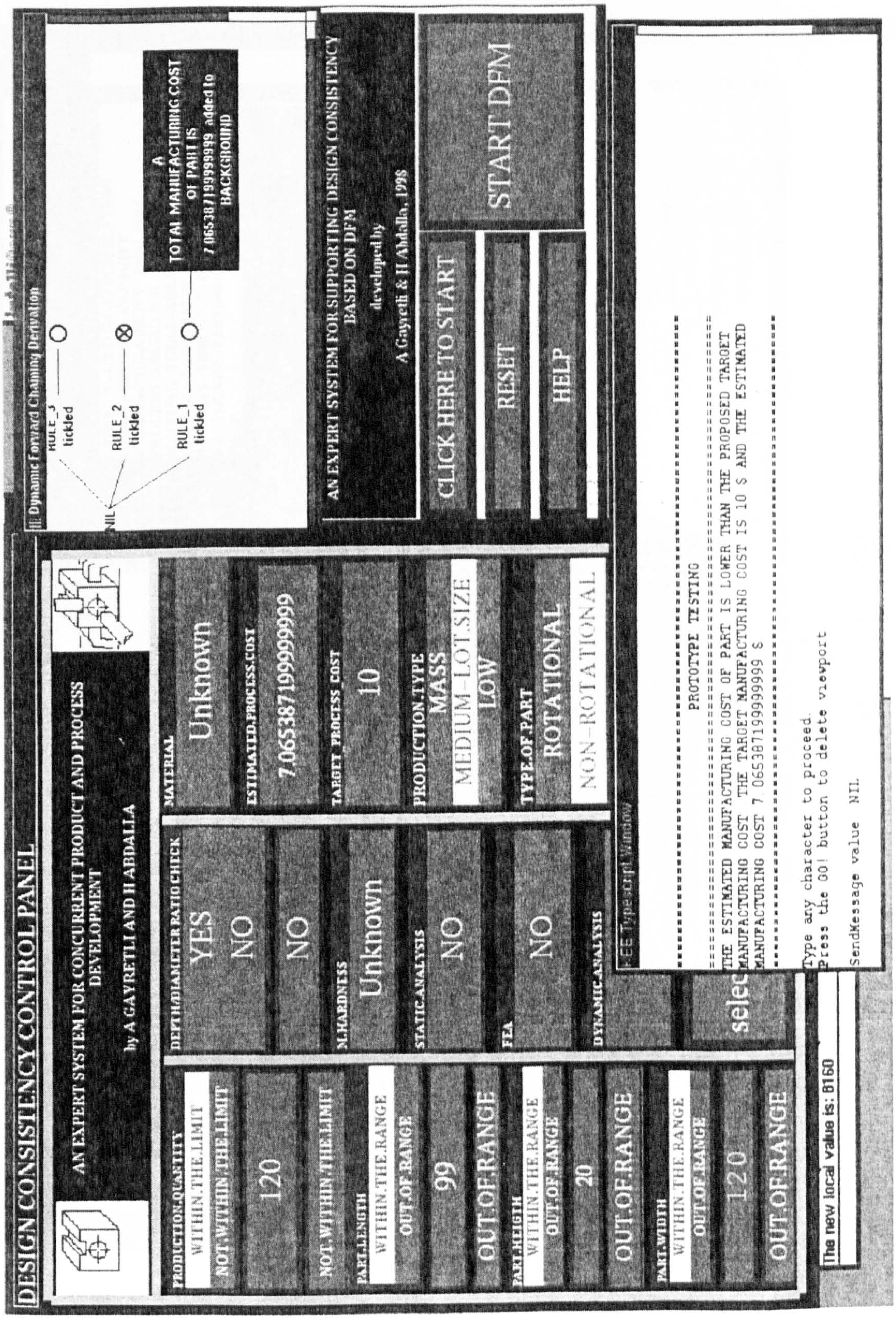

Fig. 12 Consistency modelling

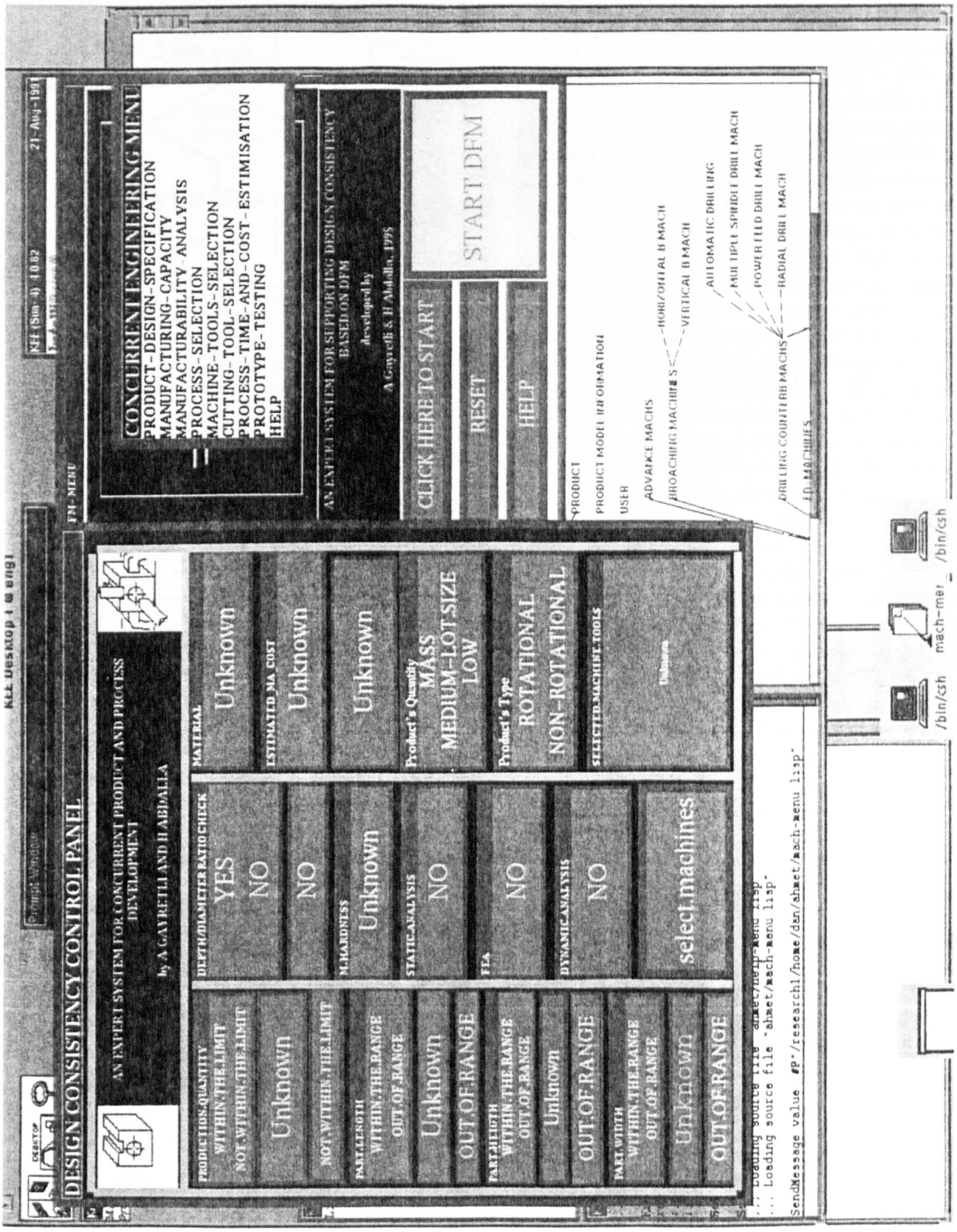

Fig. 13 User interface

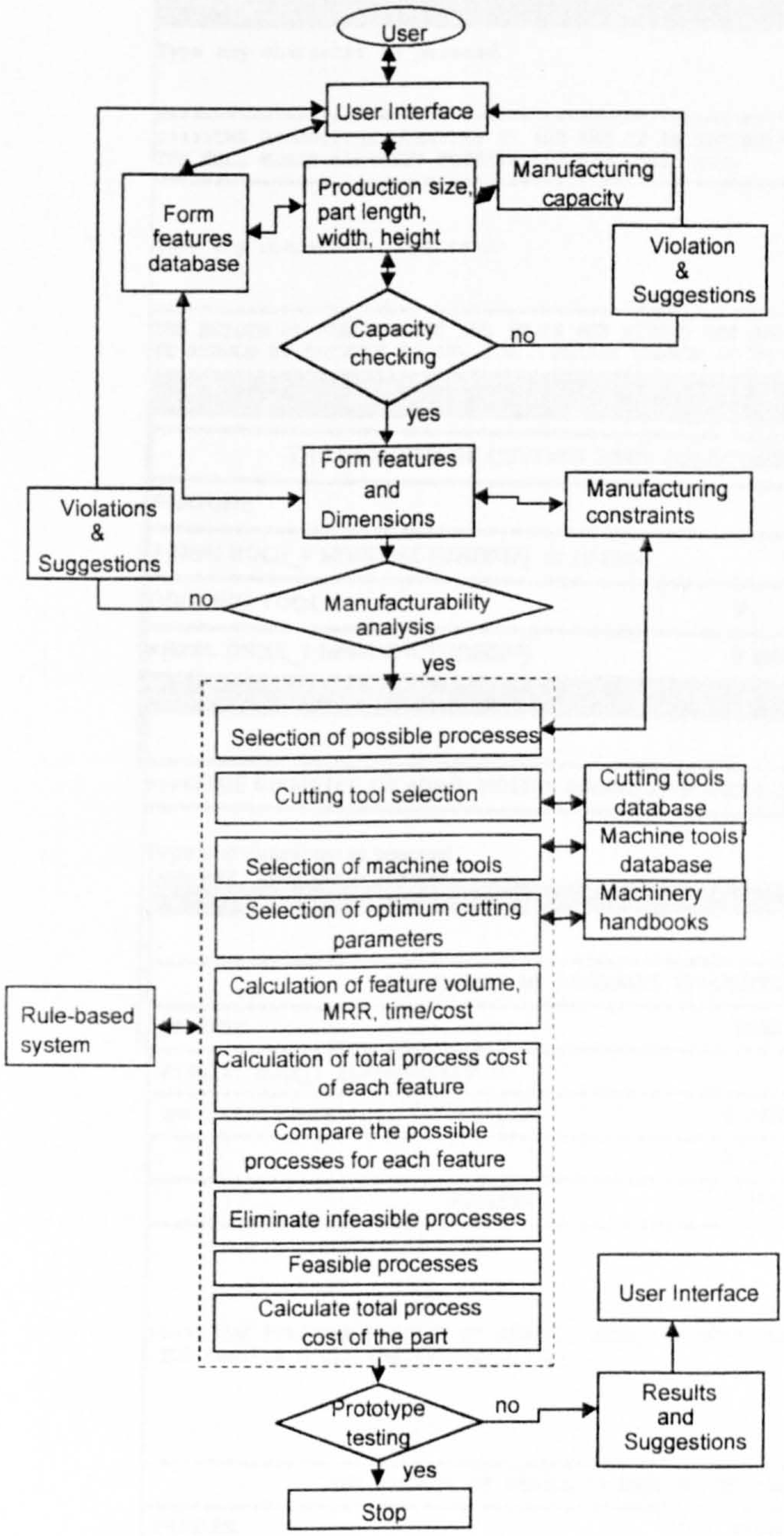

Fig. 14 Various steps involved in machining process optimization

from the system showed that drilling and end milling were the most cost effective processes for the two features (Fig. 15).

4 CONCLUSIONS

A prototype constraint-based system for the evaluation and optimization of machining processes is demonstrated in this article. The proposed system consisted of a form feature database, designer requirements, machining processes and constraints, an evaluation and optimization module and a user interface.

The integration of various issues of the product life cycle in a more consistent manner at the early design stages has been seen as one of the major achievements in this work. This integrated system enables users to design a product that satisfies most of the requirements arising from the life cycle issues at low cost, less lead time and higher quality. This can only be achieved through the use of the state-of-the-art of a fully integrated IT system. Available systems cannot offer a complete solution to the integrated product development owing to the limitations on consideration of requirements of various life cycle domains, which necessitates complex and timely interactions between these various domains. The integrated prototype constraint-based system presented in this article has taken care of most of the problems mentioned earlier, and thus facilitates successful implementation of concurrent product and process design. The system enables designers concurrently to design successful products in an interactive design environment with complete product and process design satisfaction. The integration of various issues of product life cycle such as part representation, product design specification, manufacturability analysis, process selection and optimization, manufacturing capacity checking, process cost/time estimation, machine and cutting tool selection and prototype testing has been achieved.

Information from different design areas was organized in the form of objects, rules and constraints in a knowledge base in order to achieve effective use of the life cycle information to carry out various design analyses. The knowledge base allows designers to include other life cycle requirements.

A rule-based system has been developed to access the life cycle information in the knowledge base, and to carry out design analysis such as the evaluation of form features and the optimization of the selected feasible processes based on the given requirements (i.e. production volume, lot time, tool cost and process cost and time). The integration of production rules with object-oriented programming was established in the rule classes in order to reduce the size of rule classes, create more powerful rule application and make the system more flexible and efficient.

A user-friendly interface, which consists of menus for design analysis and a design consistency panel for monitoring inconsistencies, has been developed for providing designers with complete results of the analysis, consistency monitoring and conflict resolution. Since the developed system is very flexible, the involvement of other activities of the product life cycle can easily be incorporated in the design process. The process selection and optimization module, which is the major part of the developed system, provides designers with the design of products concurrently, selection of machining processes and evaluation and optimization of those processes.

The process selection and optimization module enables the designers to carry out real-time cost estimation and generation of feasible process plans, and deal with conflict

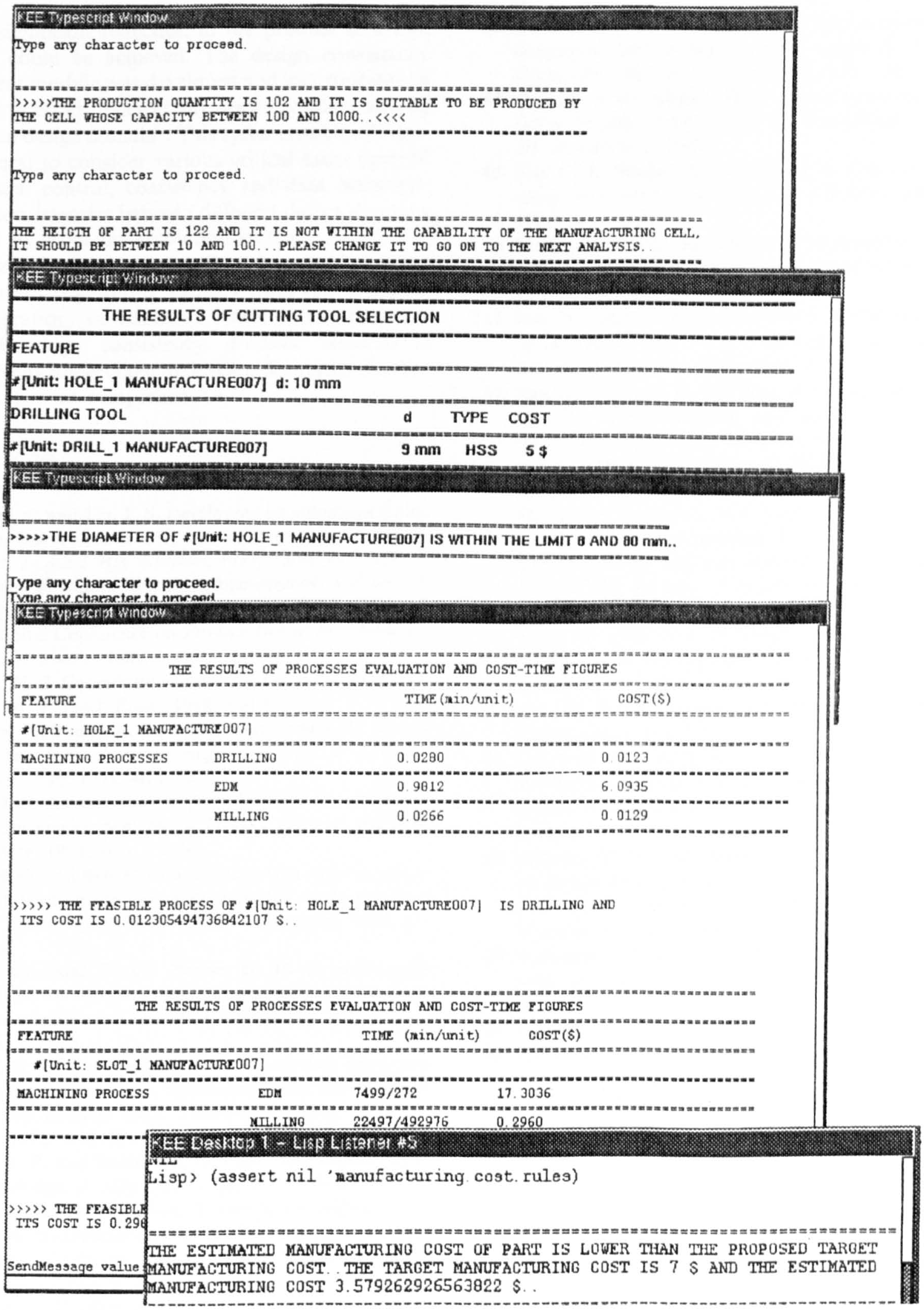

Fig. 15 Sample of system results

situations using a constraint-based system at the early design stages. It also encompasses a rule-based algorithm for estimation and optimization of machining processes.

The rule-based algorithm provides the evaluation of available processes for the features of parts in terms of user requirements and process time/cost. The designers are provided with a complete report on the results of the process selection, time/cost estimation and optimization in order to ensure the feasibility of the part. Since the results drawn from the system are promising, using this system a significant reduction in the product cost and lead time could be achieved. The design consistency management module was developed and incorporated in the system in order to detect any design conflicts among the different design domains. This system enables designers in general to consider various critical tasks (overall coordination, control, consistency and data integrity). Design inconsistencies between different design domains are solved by a conflict resolution system.

This research work has contributed to implementing the concurrent engineering strategy from four perspectives: integration, optimization, information management and design consistency. Further research is currently being undertaken to develop the system further and make it more comprehensive.

REFERENCES

1 **Ou-Yang, C.** and **Lin, T. S.** Developing an integrated frame work for feature-based early manufacturing cost estimisation. *Int. J. Advd Mfg Technol.*, 1997, **13**(9), 618–629.

2 **Huthwaite, B.** Manufacturing competitiveness and quality by design: ICD/FOCUS method. In Proceedings of Fourth International Conference on *Product Design for Manufacture and Assembly*, 1989.

3 **Abdalla, H. S.** Concurrent engineering for global manufacturing. *Int. J. Prod. Econ.*, 1998, 1–10.

4 **O'Grady, P., Young, R. E., Greef, A.** and **Smith, L.** An advice system for concurrent engineering. *Int. J. Comput. Integrated Mfg*, 1991, **4**(2), 63–70.

5 **Noble, J. S.** An approach to overall design consistency in concurrent engineering. *Int. J. Flexible Automn and Integrated Mfg*, 1993, **1**(1), 25–36.

6 **Karacali, O.** and **Bell, R.** Concurrent design expert application with CAE driven information models. In Proceedings of 31st International MATADOR Conference, 1995, pp. 479–484.

7 **Balasubramanian, S.** and **Norrie, D. H.** A multi-agent architecture for concurrent design, process planning, routing, and scheduling. *Concurrent Engng: Res. and Applic.*, 1996, **4**(1), 7–15.

8 **Lander, S. E.** and **Corkill, D. D.** Designing integrated engineering environments: blackboard-based integration of design and analysis tools. *Concurrent Engng: Res. and Applic.*, 1996, **4**(1), 59–70.

9 **Dewhurst, P.** and **Boothroyd, G.** Early cost estimating in product design. *J. Mfg Syst.*, 1998, **7**(3), 183–191.

10 **Thurston, D.** and **Carnahan, J.** Intelligent evaluation of designs for manufacturing cost. In *Concurrent Engineering: Automation, Tools, and Techniques* (Ed. A. Kusiak), 1993, pp. 401–443 (John Wiley, New York).

11 **Taiber, J. G.** Development of an optimisation method for determination of process sequences considering prismatic workpieces. *Trans. ASME, Comput. in Engng*, 1994, **1**, 271–280.

12 **Tappeta, V. R.** and **Ranaud, E. J.** A comparison of equality constraints formulation for concurrent design optimisation. *Concurrent Engng: Res. and Applic.*, 1997, **5**(5), 253–261.

13 **Downlatshahi, S.** and **Ashok, M. S.** Design optimisation in concurrent engineering: a team approach. *Concurrent Engng: Res. and Applic.*, 1997, **5**(5), 145–154.

14 **Gayretli, A.** and **Abdalla, H.** An expert system for manufacturing process optimisation. In Proceedings of *TMCE '98*, Manchester, 1998.

15 **Fen, C. J., Kusiak, A.** and **Huang, C.** Cost evaluation in design with form features. *Comput.-Aided Des.*, 1996, **28**(11), 879–885.

16 **Shaikh, M. A.** and **Hansotia, B. J.** Minimisation of drilling cost: a closed-form solution. *Comput. and Ind. Engng*, 1992, **23**(1–4), 443–446.

17 **Das, D. Gupta, S. K.** and **Nau, D. S.** Reducing set-up cost by automated generation of redesign suggestions. *Trans. ASME, Comput. in Engng*, 1994, **1**, 159–170.

18 **Das, D., Gupta, S. K.** and **Nau, D. S.** Estimation of set-up time for machined parts: accounting for work-holding constraints using a vice. In Proceedings of the Computers in Engineering Conference and the Engineering Database Symposium, 1995, pp. 619–631 (American Society of Mechanical Engineers, New York).

19 **Luong, L. H. S.** and **Spedding, T.** An integrated system for process planning and cost estimation in hole making. *Int. J. Advd Mfg Technol.*, 1995, **10**, 411–415.

20 **Pham, D. T.** and **Gologlu, C.** Machining set-up planning based on evaluation of feature relations and fixturing constraints. In *Application of Artificial Intelligence in Engineering XII* (Eds R.A. Adey, G. Rzevski and R. Teti), 1997, pp. 35–38 (Computational Mechanics Publications, Southampton, Boston).

21 **Lee, I. B. H., Lim, B. S.** and **Nee, A. Y. C.** IKOOPS: an intelligent knowledge-base object-oriented process planning system for the manufacture of progressive dies. *Expert Syst.*, 1991, **8**(1), 19–31.

22 **Abdalla, H. S.** and **Knight, J.** An expert system for concurrent product and process design of mechanical parts. *Proc. Instn Mech. Engrs, Part B, Journal of Engineering Manufacture*, 1994, **208**(B3), 167–172.

23 **Hashemian, M.** and **Gu, P.** A constraint-based system for product design. *Concurrent Engng: Res. and Applic.*, 1995, **3**(3), 177–185.

24 *Sun Common Lisp 4.0 Object System Guide*, 1990.

25 *Machining Data Handbook*, 3rd edition, 1980, Vols 1–2 (Metcut Research Associations Inc.).

26 **Ostwald, P. F.** *AM Cost Estimator*, 4th edition, 1988 (Penton Publishing).

27 **Chang, T. C.** and **Wysk, R. A.** *An Introduction to Automated Process Planning System*, 1985 (Prentice-Hall, Englewood Cliffs, New Jersey).

28 **Bralla, J. G.** *Handbook of Product Design for Manufacturing*, 1986 (McGraw-Hill, New York).

29 **Choi, H. S.** and **Park, K. H.** Shop-floor scheduling at shipbuilding yards using the multiple intelligent agent system. *J. Intelligent Mfg*, 1997, **8**(6), 505–515.

30 **Berrais, A.** Knowledge-based expert systems: user interface implications. In *Advances in Computational Structure Technology*, 1996, pp. 185–195 (Civil-Comp Press, Edinburgh).

31 **Chang, T. C.** *Expert Process Planning for Manufacturing*, 1990 (Addison-Wesley).

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An object-oriented constraints-based system for concurrent product development

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Abstract

This research work aims to develop an intelligent constraint-based system that enables designers to consider at the early stages of the design process all activities associated with product's life cycle. One of the most important aspects of these activities is the evaluation and optimisation of manufacturing processes that require various type of information from the different aspects of product's life cycle. This research article discusses the development of a prototype system for manufacturing process optimisation using a combination of both mathematical methods and constraint-programming techniques. This approach enables designers to evaluate and optimise feasible manufacturing processes in a consistent manner as early as possible during the design process. This helps in avoiding unexpected design iterations that wastage a great amount of time and effort, leading to longer lead-time. The development process has passed through the five major stages: Firstly, an intelligent constraint-based design system for concurrent product and process design has been developed. Secondly, a manufacturing process optimisation module has been constructed. Thirdly, the product features, processes, cost, time and constraints to be used for carrying out various design tasks has been represented in the format of constraints, frames, objects, and rules. Fourthly, the process optimisation and evaluation rules for the selection of feasible processes for complex features, and finally, the information management system that ensures consistency in information exchange and decision making activities have been developed.

Keywords: Feature-based design; Object-oriented programming; Concurrent engineering; Process optimisation; Cost estimation; Constraints; Knowledge-based systems

1. Introduction

Concurrent engineering as a philosophy aims to address the consideration of different life cycle issues of a product at early stages of the design process in order to analyse the factors affecting manufacturing processes. Recently, concurrent engineering has placed greater emphasis on the automation and optimisation of manufacturing processes due to its major effect on product cost. Huthwaite [1] stated that typical product cost includes 50% materials, 5% product development, 30% overheads and 15% labour. He also mentioned that almost 70% of total product cost is considered at the early stage of the design process. There are many constraints related to part features, feature-process relations, machine tools, cutting tools, cost and time in concurrent product development.

The other aspects of the product life cycle have an impact on process cost. Therefore, the constraints of the product's life cycle issues also have to be involved in process evaluation and optimisation process to reach a cost-effective design in the early stages of the design phase. Representing these constraints in an efficient format is very important to evaluate and optimise the design effectively and to prevent users from being engaged in time-consuming iterations process. To achieve an effective management of those constraints, efficient and timely communication network system should be provided within different design and manufacturing areas. This requires the critical consideration of various tasks such as overall coordination, control, consistency, and data integrity to prevent costly design iterations. This can be achieved through the integration of different design areas through establishing LANs within the organisation in a consistent manner. Such integration should include a strategy for conflict resolution to avoid disagreements within the different activities or areas. Research work in

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AN INTELLIGENT DESIGN ENVIRONMENT FOR CONCURRENT PRODUCT AND PROCESS DESIGN

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ABSTRACT

An intelligent constraint-based system for concurrent product development, which enables designers to consider at the early design stages all downstream activities of the product's life cycle has been presented in this research article. These activities (i.e. product design specification, and material selection, manufacturing process selection and optimisation, time/cost estimation, and machine tool selection) must be integrated in order to achieve a successful product design. The involvement of various requirements arising from the different life cycle perspectives has to be incorporated into the design phase. This requires the consideration of complex interactions, decision-making activities, and data sharing which can result in inconsistencies between these life cycle domains. Thus, the representation of these requirements in efficient format is very essential for carrying out different design tasks in a consistent manner. Various knowledge representation techniques such as constraints, production rules, and object-oriented programming have been used for modelling of different requirements of the life cycle perspectives. The developed system enables designers to evaluate and optimise the design subject to the predefined criteria. An information management module with a conflict resolution mechanism has been developed and linked to the system so that effective management of information exchange and decision making activities within different design and manufacturing areas can be achieved. The system also provides designers with the consideration of various critical tasks (i.e. overall co-ordination, control, consistency, and data integrity) between different design domains to avoid inconsistencies that can cause costly design iterations.

KEYWORDS

Concurrent engineering, Process optimisation, Constraints, Cost estimation, Knowledge-based systems, Feature-based design, Information Management.

INTRODUCTION

Concurrent engineering is a systematic approach to the integrated, concurrent development of a product and its related processes to meet customer requirements. It is therefore necessary to achieve the concurrent involvement of various life-cycle perspectives into the product development process. Different information from different departments of an organisation should be clearly known and well represented in an efficient way allowing the design team to look into the design from various perspectives. Such variety of information involved into the design process needs an effective management in order to provide the design team with effective and timely communication during the design process. This means the design team can receive the right information at the right time, as well as can avoid conflicts within the design team. In order to avoid disagreements within the team a conflict resolution strategy should be developed. It should provide the designer with feedback on design violations, and decisions made on the design, justifications of the decisions, and explanations of the actions to be taken. Constraint-based systems are the tools for the management of life-cycle information to ensure the design output consistent with the design specification, and prevent the design team from conflicts. There are many requirements related to part features, feature-process relations, machine tools, cutting tools, cost and time in concurrent product development. These have to be taken into consideration to reach a cost-effective design in the early stages of design phase. The current trend pushes companies to produce low cost and high quality products to keep their competitiveness to the highest possible level. This can be achieved by the best use of manufacturing resources such as machine tools, cutting tools, labour and processes to minimise the amount of time spent adding cost. In order to achieve this, manufacturing resources, capabilities, the design model and its parameters must be represented and modelled in a way that various design analyses can be carried out. A concurrent engineering approach allows the designers to consider the factors affecting product

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A KNOWLEDGE-BASED SYSTEM FOR MANUFACTURING PROCESS OPTIMISATION

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ABSTRACT

This research article aims to develop a prototype system for manufacturing process optimisation using constraint-programming technique. This approach enables designers to evaluate and optimise feasible manufacturing processes of a design in the early stages of design process. This helps to avoid unexpected design iterations that cause wastage of a great amount of engineering time and effort, hence longer lead- time. The development process has passed through the following stages: firstly, development of a broad model for process evaluation and optimisation; secondly, modelling of product features, processes, cost, time and constraints; thirdly, building an expert system with a user interface that covers design and manufacturing knowledge. The expert system helps designer evaluate a number of processes for a part feature and calculate process time and cost in terms of designer requirements.

KEYWORDS

Process Optimisation, Cost Estimation, Knowledge-based Systems, Feature-based Design, Concurrent engineering.

1. INTRODUCTION

Concurrent engineering aims at addressing the different life cycle issues of a product in the early stages of design process. Instead of iterative product development process, considerations such as manufacturability, assembly, recyclability and maintenance are early incorporated into the design phase.

Recently, concurrent engineering has placed a greater emphasis on the automation and optimisation of manufacturing processes due to its major effect on product cost. Huthwaite (1989) stated that typical product cost includes 50% materials, 5% product development, 30% overheads and 15% labour. He also mentioned that 70% of total product is considered in the early stage of design. There are many constraints related to part features, feature-process relations, machine tools, cutting tools, cost and time in concurrent product development. These constraints have to be taken into consideration to reach a cost-effective design in the early stages of design phase. Representing these constraints in efficient format and a way is very important to evaluate and optimise design effectively and prevent designer from time-consuming iterations. This helps to improve product quality and reduce the number of redesigns, therefore leading to shorter lead-time at design stage. Previously, work has been carried out in developing methods and tools for the estimation and optimisation of manufacturing cost (Thurston and Carnahan (1993), Dewshurst and Boothroyd (1988)). A model has been developed by focusing on machining form features such as hole, slot, flat surface, chamfer, cylinder and rectangular block (Fen et al., 1996). The activities such as drilling, milling, handling, set-ups and tool change for the component can be evaluated and optimised (Das et al., 1995, Luong and Spedding, 1995, Das et al., 1994, Shaikh and Hansotia, 1992). Taiber (1994) has classified manufacturing cost optimisation of prismatic components as follows:

1. Tool cost
2. Machine tool cost

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A FEATURE-BASED PROTOTYPE SYSTEM FOR THE EVALUATION AND OPTIMISATION OF MANUFACTURING PROCESSES

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ABSTRACT

The aim of this research work is to develop an intelligent design environment that enables designers to incorporate all product and process related activities into the design phase at early stages of the design process. One of the most important aspects of these activities is evaluation and optimisation of manufacturing processes. This research article focuses on developing a prototype system for manufacturing process optimisation using a combination of mathematical methods and constraint-programming techniques. This approach enables designers to evaluate and optimise feasible manufacturing processes as early as possible during the design session. This helps to avoid unexpected design iterations that cause wastage of a great amount of engineering time and effort, hence longer lead-time. The development process has passed through the following stages: firstly, the development of an intelligent design system for manufacturing process optimisation, secondly, representation of product features, processes, cost, time and constraints; thirdly, developing the process optimisation rules for the selection of feasible processes for form features, finally, a user interface that provides designer with feedback about process selection and evaluation.

KEYWORDS

Concurrent Engineering, Process Optimisation, Cost Estimation, Knowledge-based Systems, Feature-based Design.

INTRODUCTION

Concurrent Engineering is a strategy aims to take into consideration the different life cycle issues of a product at early stages of the design process to analyse the factors affecting manufacturing processes. This analysis leads to the consideration of the automation and optimisation of manufacturing processes due to its major effect on the product cost. It has been reported that almost 70% of the product cost is considered at the early stages of design process. Therefore, many constraints related to part features, feature-process relations, machine tools have to be considered carefully to reach a cost-effective design. Representation of these constraints in efficient format is very important to evaluate and optimise the design effectively and prevent designers from time-consuming iterations. This improves product quality and reduces re-engineering work, therefore leading to shorter lead-time. Research work has recently been devoted towards developing methods and tools for the estimation and optimisation of manufacturing cost (Tappeta and Renaud, 1997; Downlathahi and Ashok, 1997; Gayretli and Abdalla, 1998). Feature-based models that focus on machining form features such as hole, slot, flat surface, chamfer, cylinder and rectangular block have been investigated by Fen et al., 1996; Ou-Yang and Lin, 1997.

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